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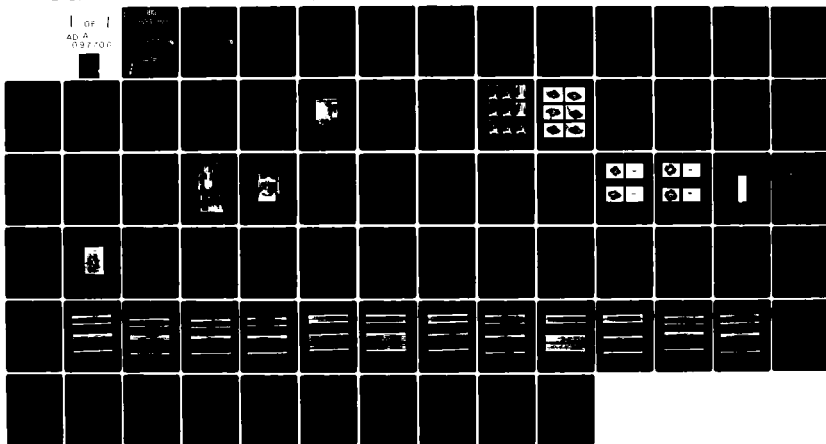
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**EXPERIMENTAL INVESTIGATION OF THE  
INTERACTION OF MOISTURE, LOW TEMPERATURE, AND  
LOW LEVEL IMPACT ON GRAPHITE/EPOXY COMPOSITES**

AD A 097 706

PREPARED BY  
K. N. LAURAITIS  
P.E. SANDORFF

**LOCKHEED-CALIFORNIA COMPANY  
BURBANK, CALIFORNIA**

FINAL REPORT  
OCTOBER 1980

DTIC  
SELECTED  
APR 8 1981

**PREPARED FOR  
NAVAL AIR DEVELOPMENT CENTER  
WARMINSTER, PENNSYLVANIA  
CONTRACT NO. N62269-79-C-0276**

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## FOREWORD

The investigation of the interaction of moisture, low temperature and impact damage and the subsequent effect on column buckling behavior reported herein was performed by the Lockheed-California Company, Burbank, California, a division of Lockheed Corporation, under Navy Contract N62269-79-C-0276. The Navy Project Engineer directing the program was E. T. Vadala of the Structural Materials Branch, Aero Materials Laboratory, Naval Air Development Center at Warminster, Pennsylvania. The program was conducted by the Structures and Materials Department of the Lockheed-California Company, with K.N. Lauraitis as Principal Investigator assisted by P.E. Sandorff.

The support and contributions of W. E. Krupp, S. Krystokowiak and R. C. Young of the Materials Laboratory and D. E. Pettit, R. LaForce and C. J. Looper of the Fatigue and Fracture Mechanics Laboratory are gratefully acknowledged.

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## SECTION I

## INTRODUCTION

1.1 PROBLEM DEFINITION

Effect of low speed impact damage on composite materials is a new and potentially significant design condition for high performance systems. In metallic structure, damage due to tool drop, small rock impact and hail (while on the ground) did not constitute a damage of major concern. However, composites generally exhibit little inelastic ductility, are sensitive to secondary stresses, and are susceptible to splitting and delamination with cracks often propagating in the fiber direction through debonding. Upon failure, energy absorption is low. Due to these fracture characteristics and the low strain to failure, composite materials generally exhibit lower impact resistance than the metals typically used for aircraft construction.

Environmental exposure may aggravate the deleterious effects of impact damage. It is well known that the mechanical properties of a polymeric matrix are susceptible to environmental degradation. Matrix cracking resulting from impact, loading or thermal cycling may provide pathways for moisture which can enter by laminar flow much more rapidly than by diffusion upon subsequent exposure to high humidity environment. Detrimental effects may also be expected because the internal tensile stress in the matrix increases with decreasing temperature, promoting crazing and the formation of microvoids. Furthermore, the cubical coefficient of expansion of epoxy polymers is approximately  $1.5 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$  and that of ice approximately  $112 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$  down to  $-54^{\circ}\text{C}$  ( $-65^{\circ}\text{F}$ ); thus, ice formation in the matrix cracks may promote crazing and crack growth on cool-down to this temperature. The possible degradation of compressive strength due to temperature and moisture has thus been one of the major concerns in the application of advanced composite systems to aircraft structure. The possibility of interactions between impact

damage and environmental factors resulting in an amplified loss in compressive strength is recognized as requiring investigation.

## 1.2 OBJECTIVE

The objective of this program was to provide an experimental evaluation of the possible interaction effects of environmental factors (specifically moisture and low temperature) with low velocity impact damage on the subsequent performance of a representative graphite/epoxy laminate under compressive load.

## 1.3 PROGRAM SUMMARY

### 1.3.1 Nature of the Impact Damage

The type of impact damage to be investigated in this program is that which is produced by low speed impact of a blunt object, such as an accidentally dropped hand tool. Specifically, the damage condition selected for study was defined as the onset of visible cracking of approximately 1 to 1½ inch diameter on one face, which would allow direct entrance of moisture into the laminate interior.

A preliminary experimental investigation of impact effects was conducted as an initial part of the program, in order to develop the technique which would produce the desired type and amount of damage consistently on replicate specimens. These results are presented in Section 4.1.

Impact damage was monitored throughout the program with Holosonic System 400 equipment, an ultrasonic inspection system providing B and C-scan data, memory storage and an oscilloscope display that was photographed for permanent record.

### 1.3.2 Evaluation of Effects

Evaluation of residual compressive strength was made by means of a plate-column test, using a compression test fixture which provided the specimen with simple transverse (pin) supports at uniformly spaced intervals. This type of test produces a column instability failure mode which can be compared

to the compression failure expected in actual structural applications. In addition, one specimen of each of the twelve different test conditions was sectioned for photomicrographic analysis of the damage caused by impact and environmental exposure.

### 1.3.3 Program Scope

The scope of the investigation was limited to one level in each of the possible variables, as follows:

Material:	AS/3501-6 graphite-epoxy
Laminate:	16-ply (+45/0/-45/0/+45/0/-45/90)s
Impact damage:	Onset of visible cracking on one face, approximately 1 to 1.5 inch diameter.
Moisture conditioning:	Exposure to 90% RH at 160°F until gain of 1.0% by weight.
Low temp. exposure:	One-half hour at -65°F, return to ambient, hold for one hour.
Moist.-temp. cycling:	Ten cycles of one hour at 90% RH and 160°F alternated with one-half hour at -65°F.
Specimen configuration:	3 x 14 inches with tabbed ends.
Residual compr. strength:	Specimen pin-supported at 0.78-inch spacing to obtain 11 bays each free to buckle as a plate column.

The main program of experiments utilized three groups of 24 specimens each. The first group was used to investigate the effect of impact damage on compressive strength evaluated with and without subsequent exposure to moisture, low temperature, and moisture-temperature cycling. The second group of specimens were moisture conditioned prior to the impact damage, and the third group was exposed to low temperature prior to impact. A total of twelve different combinations and sequences of damage and exposure was investigated.

## SECTION 2

## TEST SPECIMENS

2.1 MATERIAL

AS/3501-6 graphite/epoxy prepreg tape was procured from Hercules, Inc., Magna, Utah, Lot 1363, in November, 1979. The Hercules quality assurance data which accompanied this shipment are included in the Appendix, Table A-1. Upon receipt, acceptance tests were performed by the Lockheed-California Company QA Lab in accordance with established specifications for 350<sup>0</sup>-F curing epoxy-impregnated graphite fiber tape. Conformance to industry-recognized specifications was confirmed. The results of these tests are summarized in the Appendix, Table A-2.

2.2 Panel Fabrication and Process Verification

Two 36 x 34-inch panels, identified 1X01618 and 1X01674, and three 36 x 48-inch panels, identified 1X01619, 1X01620 and 1X01621, of 16-ply laminate with stacking sequence (+45/0/-45/0/+45/0/-45/90)<sub>s</sub> were fabricated of the AS/3501-6 prepreg to furnish stock from which the test specimens were cut. The panel identification is an autoclave number which codes the material and the process records. Autoclave curing followed specifications summarized in Table A-3 of the Appendix. The panels were inspected ultrasonically in C-scan mode, and no indications of internal flaws were found.

Analysis for fiber and resin content by weight was performed on samples of approximately one gram taken from the interior region of each panel, using techniques which (except for the larger sample size) were in accordance with ANSI/ASTM D 792-66, Procedure A-1, for specific gravity determination, and ANSI/ASTM D 3171-73, Procedure A, for fiber content. Fiber volume fraction and void content were calculated from these data using nominal values for the

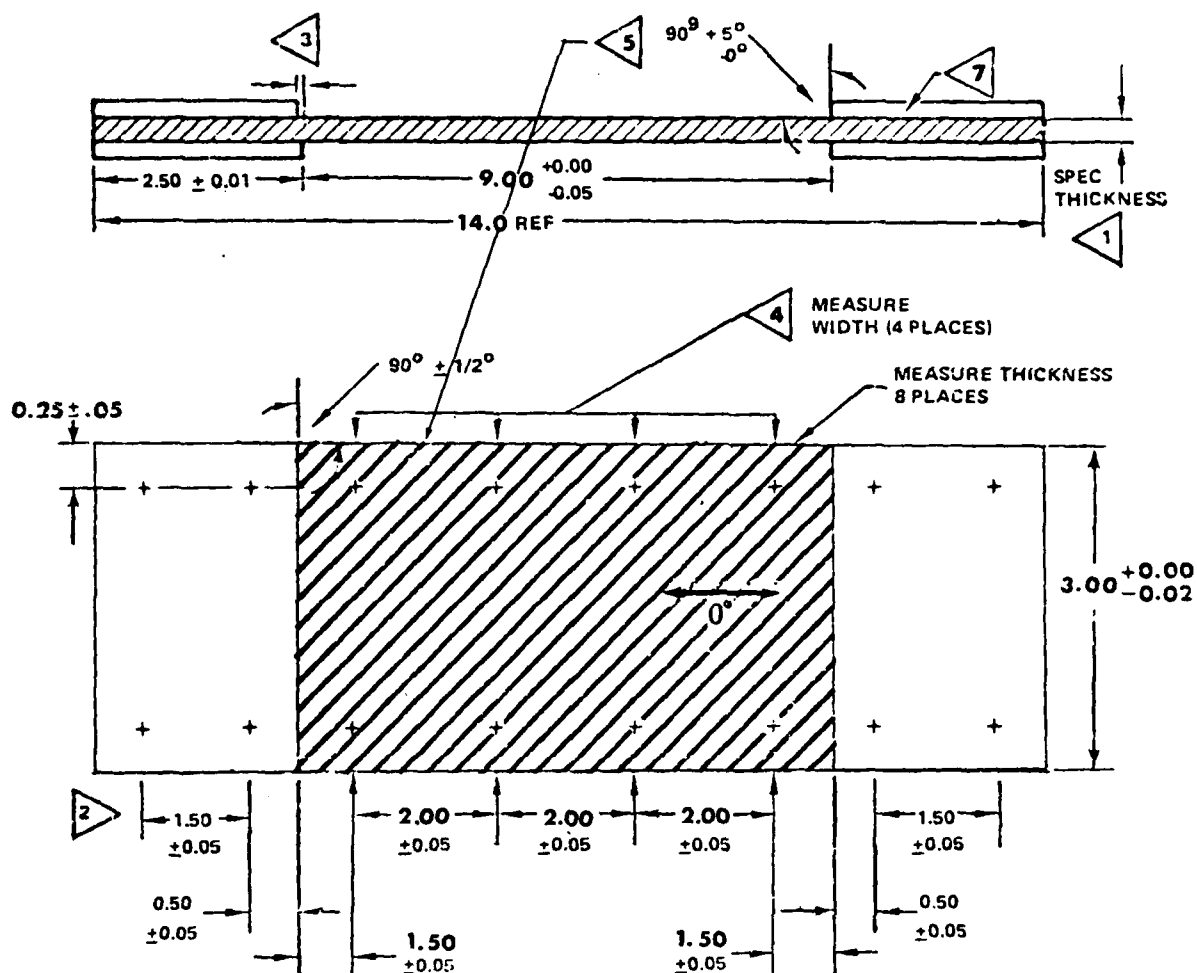
specific gravity of the fiber and the resin as supplied by the manufacturer. These results, indicating fiber volume fraction between 58 and 61 percent, are summarized in Table 2-1.

Five replicate .25 x .65-inch short-beam-shear specimens were machined at 0° orientation from the interior region of each panel. Tests were conducted in accordance with ASTM D 2344, except for the specimen thickness being the thickness of the 16-ply laminate. Results of these tests are tabulated in Table 2-2.

### 2.3 TEST SPECIMEN DETAILS

Prior to cutting specimens from a panel, a strip 1.5-inches wide was removed from all four edges and discarded, in order to avoid variations in thickness and density which sometimes occur in these regions. Three by 14-inch specimen blanks were then cut and specimens were fabricated and inspected according to the specifications of Figure 2-1.

Twenty-four specimens obtained from panel 1X01618 were used exclusively for the preliminary impact damage study. Four of these (identified in Section 4.1) differed from Figure 2-1 in that the long axis was oriented 90° to the laminate axis. The 36 x 48-inch panels were first cut into three subpanels each, identified A, B, and C, and each subpanel then cut into ten 3 x 14-inch specimen blanks having the 14-inch dimension parallel to the laminate axis. The specimens were individually identified by the last two digits of the panel autoclave number, the subpanel letter and the sequence of removal. A randomization procedure based on a computer-generated sequence was then used to assign the specimens to specific use in the program. In an early state of the experimental work, it was decided to revise the geometry of the residual column strength test, for reasons explained in Section 4.2. This decision resulted in fabricating additional specimens to replace those which had been tested using the longer column support length. For this purpose, twenty new specimens were cut from Panel 1X01674. These could no longer be distributed among the various tasks of the program, but were assigned by a random selection process to the three test conditions which were to be repeated using the final column support length used on the remainder of the program.



- 8 SPECIMENS TO BE FLAT OVER THE ENTIRE 14.0 INCH LENGTH WITHIN 0.01 INCHES.
- 7 TAB EDGES TO BE PARALLEL TO SIDES OF SPECIMEN WITHIN 0.02 INCHES. OVERHANG NOT TO EXCEED 0.15.
- 6 THE TAB AND SPECIMEN BONDING SURFACES TO BE THOROUGHLY SOLVENT CLEANED USING METHYL-ETHYL-KETONE PRIOR TO BONDING. A 350°F CURING ADHESIVE IS TO BE USED AND MUST COVER ENTIRE SURFACE UNIFORMLY.
- 5 MACHINED SURFACES TO BE RMS 50 OR BETTER. NO EDGE DAMAGE OR FIBER SEPARATION SHOULD BE VISIBLE.
- 4 MEASURE SPECIMEN WIDTH 4 PLACES. WIDTH MUST NOT VARY BY MORE THAN 0.004 INCHES
- 3 MISMATCH OF TABS FROM SIDE TO SIDE NOT TO EXCEED 0.01 INCHES.
- 2 TABS TO BE CUT FROM A 6 FLY LAMINATE FABRICATED FROM PREPREG OF 1581 GLASS FABRIC IN A 350°F CURING EPOXY. TAB PLUS ADHESIVE THICKNESS MUST NOT VARY SIDE TO SIDE OR END TO END BY MORE THAN 0.01 INCH AS MEASURED 8 PLACES.
- 1 SPECIMEN THICKNESS TO BE WITHIN ±0.003 INCHES OF THE AVERAGE OF 8 THICKNESS MEASUREMENTS.

Figure 2-1: Specimen Configuration

TABLE 2-1  
FIBER AND VOID CONTENT OF PANEL MATERIAL

Panel ID	Density gm/ml	Average Density gm/ml	Resin Content By Weight %	Fiber Content By Volume*	Calculated Void Content*
1X01618	1.587	1.586	34.0	58.4	1.2
	1.586				
1X01619	1.584	1.579	33.4	58.6	- .4
	1.574				
	1.581				
1X01620	1.587	1.582	32.8	59.2	- .3
	1.582				
	1.577				
1X01621	1.593	1.590	31.3	60.9	- .3
	1.587				
	1.591				
1X01674	1.604	1.598	31.9	60.5	0.5
	1.590				
	1.599				

\*Fiber volume and void content calculations based on nominal values of density of 1.796 gm/ml for fiber and 1.262 gm/ml for resin, as stated by manufacturer. Normal variations from these values frequently result in negative values for calculated void content.

TABLE 2-2  
SHORT BEAM SHEAR TEST RESULTS

Panel ID	Width in.	Thickness in.	Failure Load lbs.	SBS Stress psi.
1X01618				
1	.250	.094	323	10300
2	.248	.094	328	10600
3	.246	.093	282	9200
4	.249	.093	343	11100
5	.249	.093	324	10400
				10300 +500
1X01619				
1	.250	.097	339	10500
2	.249	.096	341	10700
3	.249	.096	395	12400
4	.249	.097	337	10400
5	.250	.096	352	11000
				11000 +500
1X01620				
1	.249	.093	370	12000
2	.251	.093	399	12800
3	.250	.093	343	11000
4	.249	.093	392	12700
5	.252	.093	333	10700
				11800 +700
1X01621				
1	.251	.092	316	10300
2	.252	.093	291	9300
3	.251	.092	338	11000
4	.251	.091	311	10200
5	.250	.092	303	9900
				10100 +400
1X01674				
1	.243	.089	259	8980
2	.242	.089	281	9760
3	.244	.089	265	9150
4	.234	.090	269	9600
5	.235	.089	273	9790
				9460 +250

Summations indicate mean + probable error.

## SECTION 3

## EXPERIMENTAL METHODS

3.1 IMPACT LOADING

Impact damage was produced by the impact of a steel mass dropped from a drop tower. The drop tower consisted of a teflon guide tube mounted in a support frame. The drop height was adjustable and preset by a pin extending through the teflon guide tube. Available impactors included a series of one-inch diameter steel cylinders providing a selection as to mass and diameter of impactor head. All impacts were conducted at room temperature in an ambient laboratory air environment. The specimen support, which rested on a flat concrete floor, was positioned to obtain impact at the intersection of the specimen center lines. The impact tower and the impactor are shown in Figure 3-1, and the specimen support is detailed in Figure 3-2.

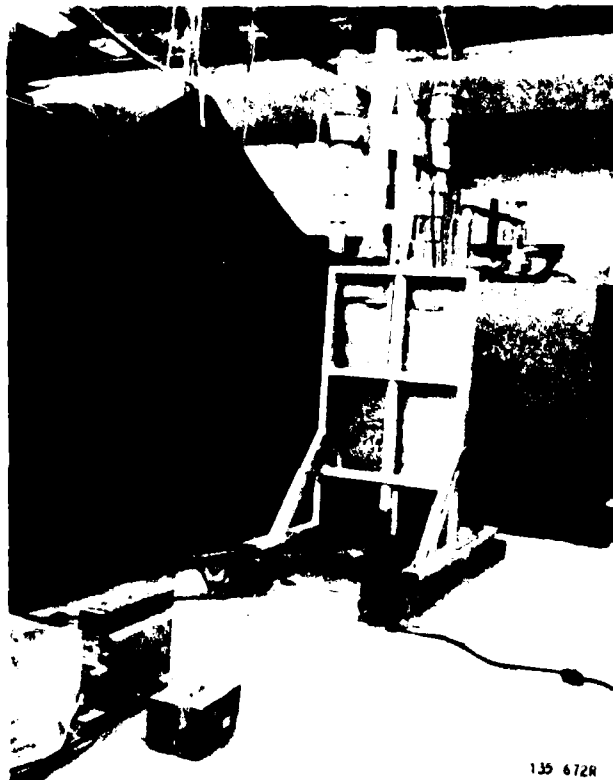
3.2 INSTRUMENTATION AND DATA ACQUISITION3.2.1 High Speed Photography

A 16-mm high-speed camera operating at 400 frames per second was used to record motion of the impactor and the specimen surface just prior to, during, and subsequent to the impact. Optical timing pulses at a precise frequency of 100 per second were simultaneously recorded on the margin of the film. The photographic records of impactor motion were analyzed to obtain impactor positions (d) above the impact point at time intervals ( $\Delta t$ ) before, and after, the impact. Impact velocity and rebound velocity were then calculated by the relation

$$v_o = \frac{g}{\Delta t} + \frac{g}{2} \Delta t$$

where  $g = 32.2$  fps. This method provides accurate values since it minimizes any disturbing effects due to variations in release and friction of the guide

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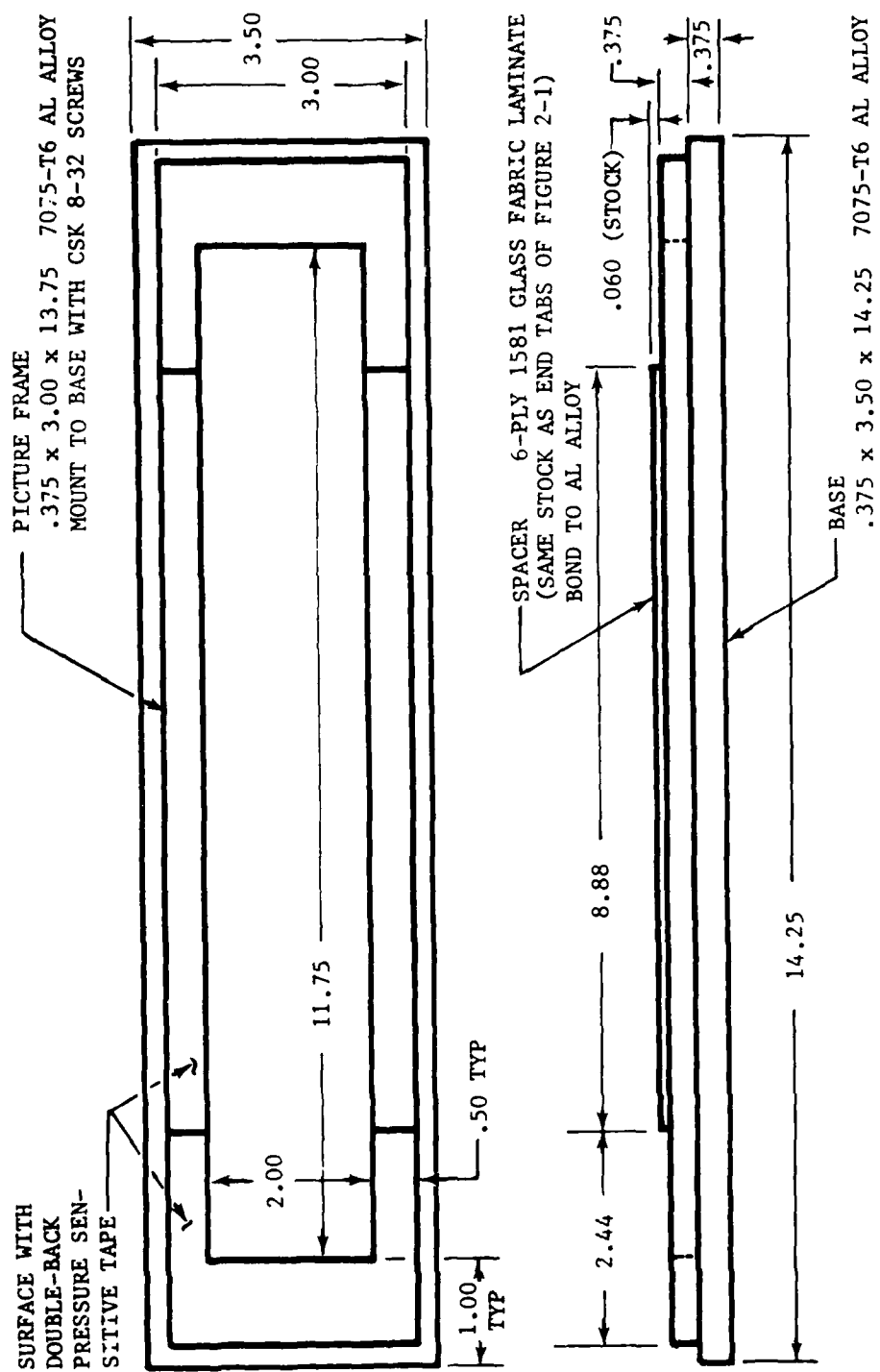


FIGURE 3-2: SPECIMEN SUPPORT DETAIL

tube. A sequence of photographs taken during a representative impact test showing the motion of the impactor and the specimen is presented in Figure 3-3.

### 3.2.2 Ultrasonic Evaluation of Damage

The extent of the impact damage produced in each specimen was determined by ultrasonic inspection. For this purpose ultrasonic imaging equipment purchased commercially as the Holscan System 400, Holosonics Company, San Rafael, California, was used. This equipment provided the capabilities of real-time ultrasonics inspection involving B-scan, C-scan, and three dimensional displays. The basic system used in this program also incorporated the following capabilities:

- a. The "flex arm" manual mount for the transducer was replaced with a power driven scanner mount with digital scanner controls interfaced with the System 400 electronics.
- b. A digital memory, real time image display, electronic processor, and dual mode oscilloscope were interfaced with the System 400 electronics to provide a digital memory storage unit to retain and provide subsequent display of the data in C-scan and in associated B-scan format, as well as in 3-D isometric format.
- c. A vertical mounting and coupling system was attached to the transducer/digital scanner. Inclusion of this system made it possible to scan test specimens in a vertical position, thus eliminating the need to immerse the specimen in water for extended periods such as occurs during normal C-scan, the water contact being limited to the water column directly in front of the scanning transducer.

The C-scan was the most useful for delineating damage size. Permanent records of the damage were obtained as Polaroid photographs of the oscilloscope C-scan display. Representative records are presented in Figure 3-4. Damage measurements of the maximum damage were made from these photographs as shown in Figure 3-5. In order to determine the scale of the photographs, a special graphite/epoxy calibration block was machined with two parallel milled cuts running vertically and two horizontally across the block. Width and spacing of the slots were

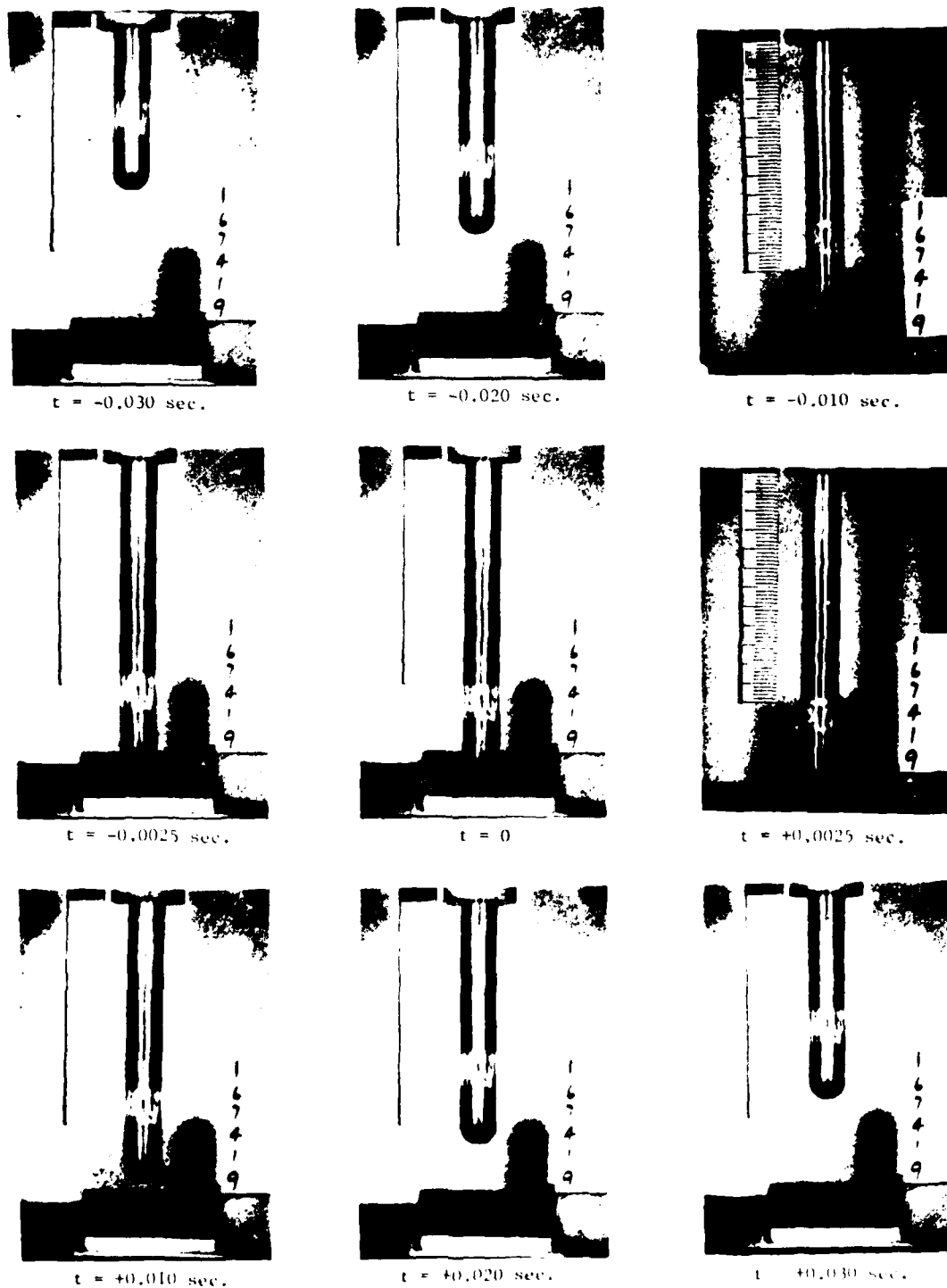
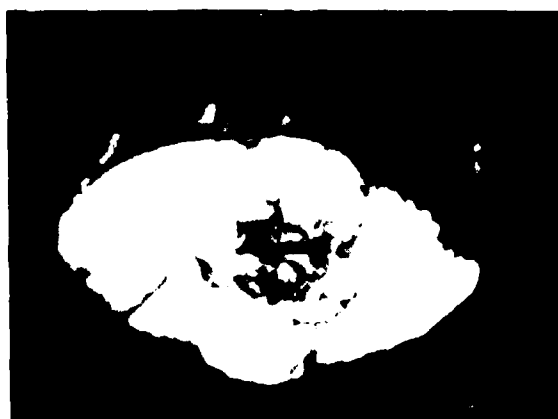


Figure 3-3: Selected Frames from High Speed Motion Pictures Taken of Impact of Specimen 74-19 from Group B-1. (Time referenced approximately to maximum deflection.)



1X01621C-8, from Gp A1  
1.01 x 1.62 in.



1X01620A-7, from GP A2  
0.98 x 1.66 in.



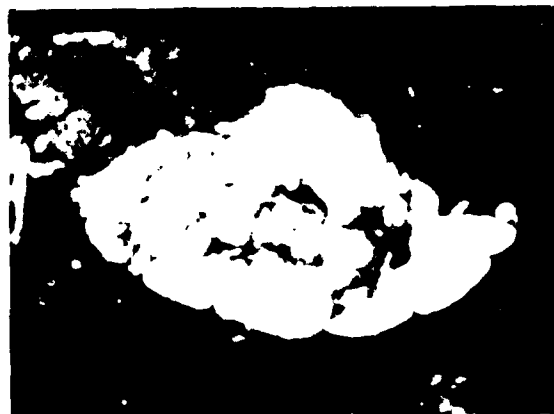
1X01619A-9, from Gp A3  
0.98 x 1.74 in.



1X01621A-4, from Gp A4  
1.07 x 1.66 in.



1X01620A-3, from Gp C3  
1.02 x 1.64 in.



1X01619B-1, from GP C1  
1.01 x 1.79 in.

Figure 3-4: Representative Ultrasonic C-scan (Holscan) Photographic Records Obtained in the Main Program

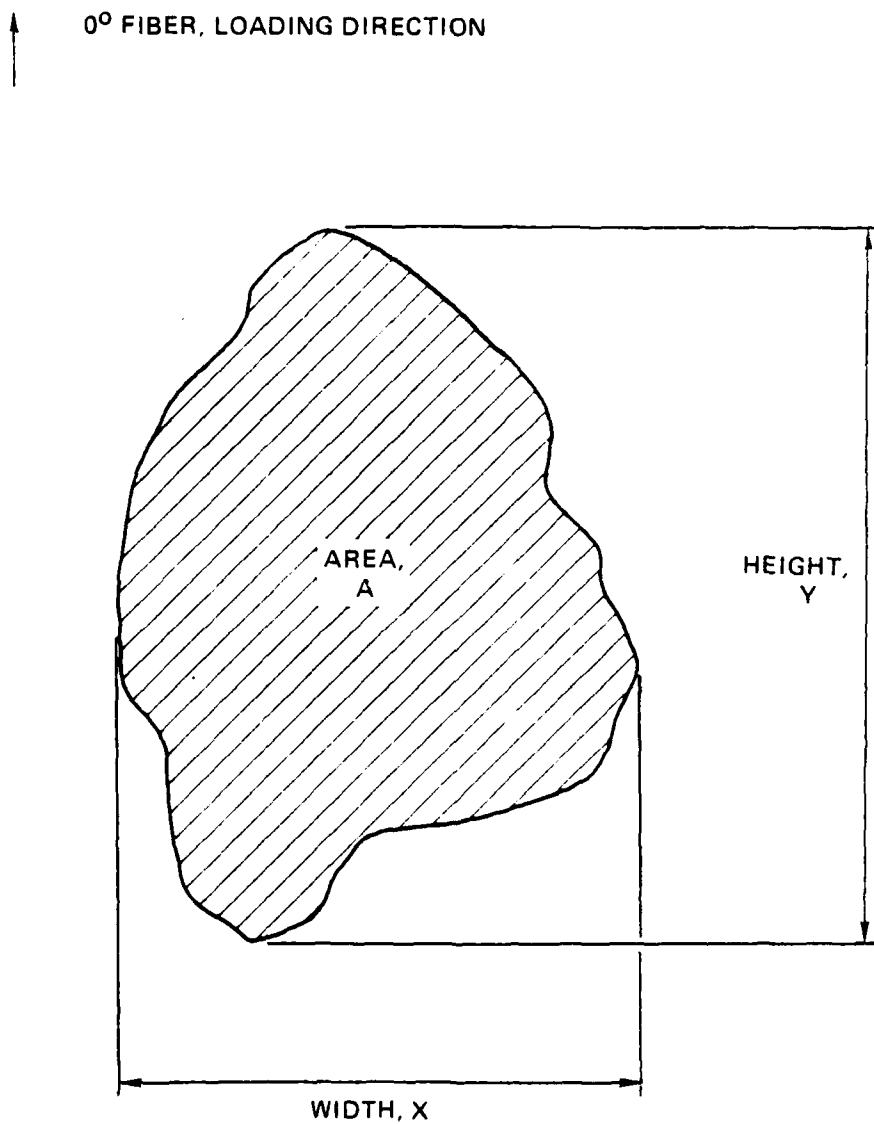


Figure 3-5: Illustration of Methods of Damage Zone Height and Width Measurement

measured with a tool maker's microscope. The block was then scanned with the Holscan unit, photos were taken of the TV monitor display, and the spacings measured from the photo to obtain scaling factors as described in Reference 1.

### 3.2.3 Strain Gage Instrumentation

A number of specimens were instrumented with electrical resistance foil strain gages of 0.25-inch gage length mounted on the rear surface directly opposite the impact point, to provide dynamic records of the strain parallel to the laminate axis during impact. A calibration of the measured strain in terms of the force introduced by the head of the impactor was obtained by "static" tests conducted in a universal testing machine at several different crosshead speeds. The results of these tests, presented in Figure 3-6, indicate a force/strain relationship of 51000 lb. per unit strain. For the low speed impact test conditions, static calibration is believed to provide a good approximation to the force applied up to incipient failure. Once fracture has initiated, local propagation rates and mechanisms may be expected to differ importantly, and no correlation between the load-strain relationships as obtained statically and dynamically could be expected. But when fracture occurs, the applied force has approached or reached its peak; static calibration of the strain gage response therefore provides an approximate measure of the peak force.

In tests in which strain gage data were obtained, a centralized data acquisition, recording, and processing system was used which provides a demonstrated overall accuracy of one percent through null calibration of individual sensors and digitalization of data. A typical strain record obtained in a representative impact test is presented in Figure 3-7; here the horizontal scale is proportional to time. This record is interpreted as indicating failure at a strain of .0123 in/in, which (from the static calibration) corresponds to a force of 560 lb.

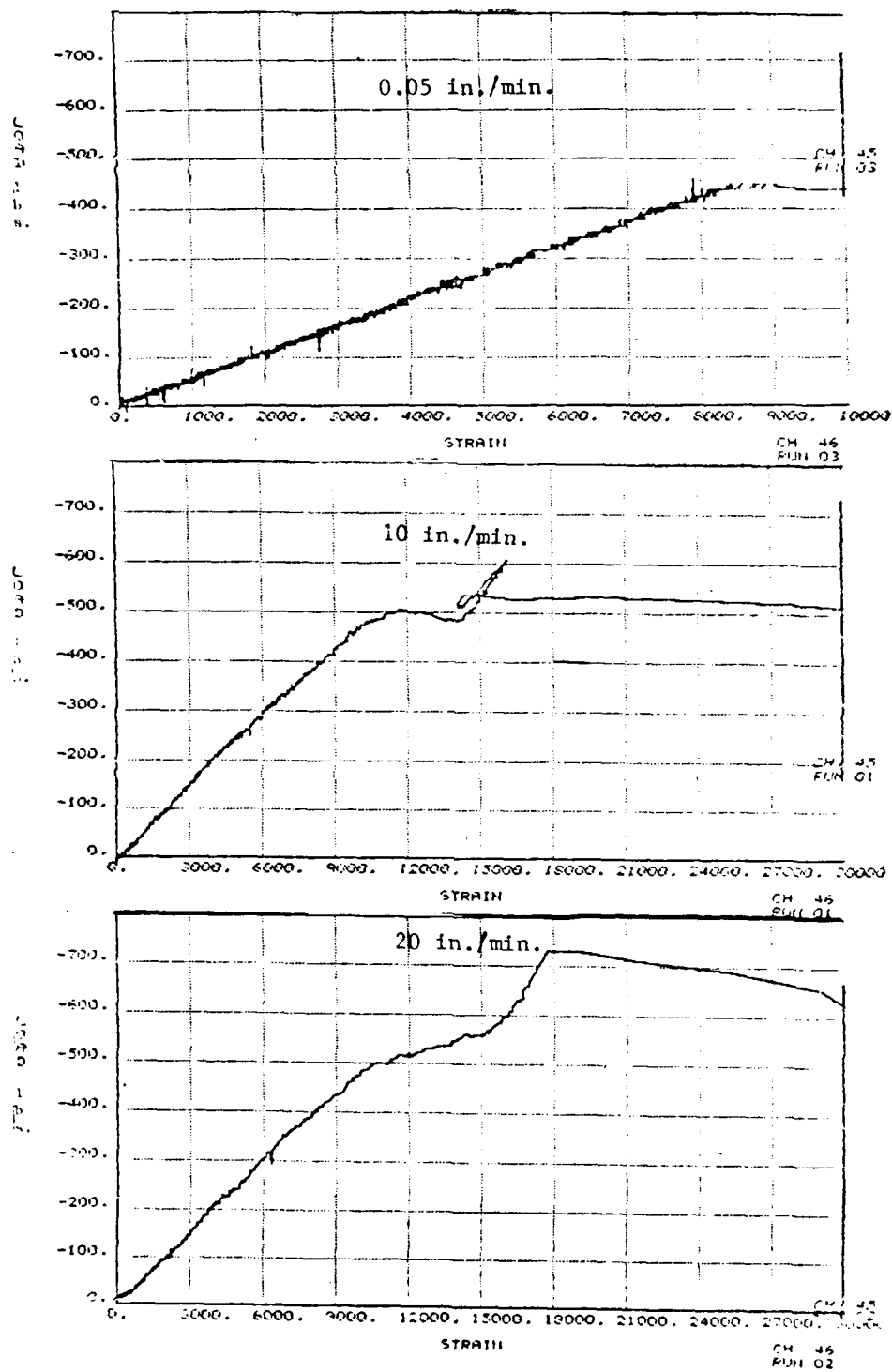


Figure 3-6: Static Calibrations of Force Applied By Impactor Head in Terms of Measured Strain on Under-side of Specimen.

NADC IMPACT  
 TEST 11213 RUN 092  
 Y-AXIS CH 0000 YMAX  
 X-AXIS CH 0000 XMAX  
 6.14 YMIN  
 7600.00 XMIN  
 -0.10  
 7500.00

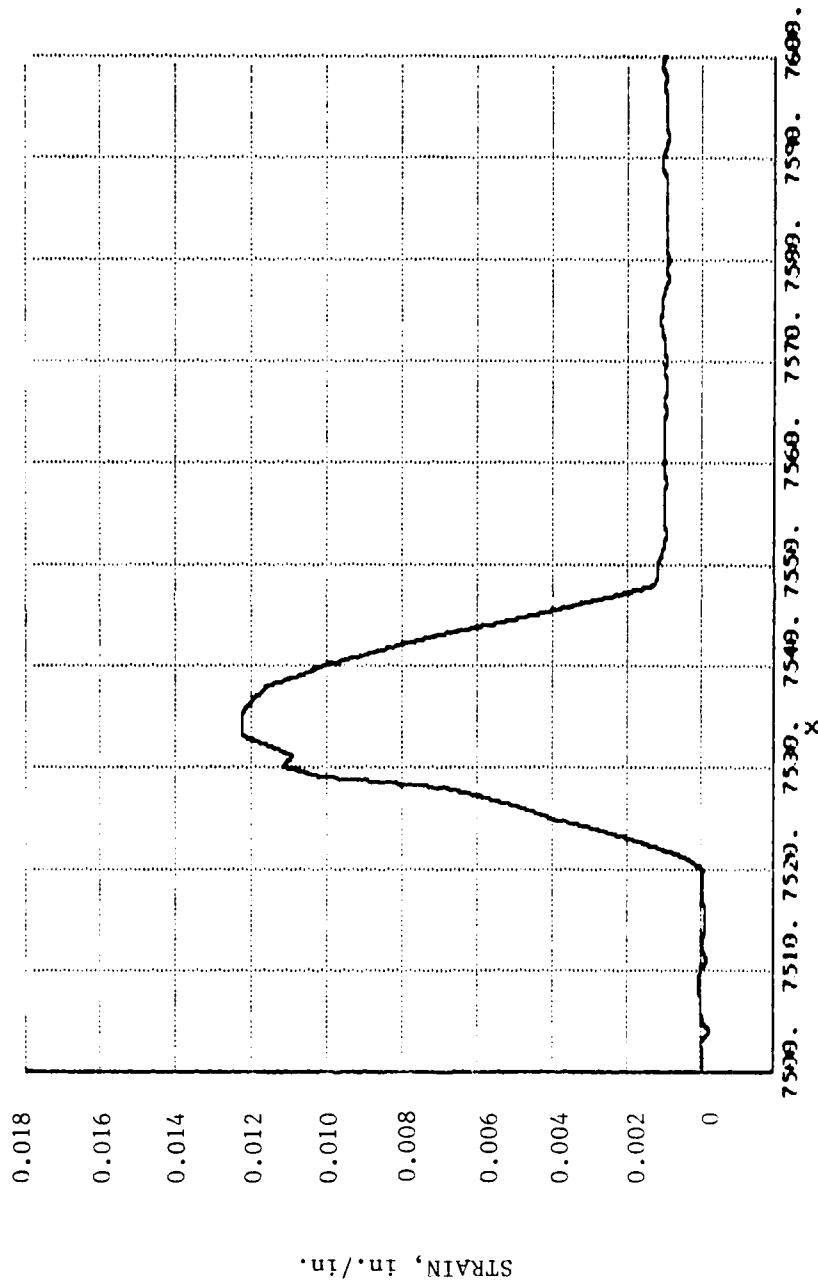


Figure 3-7: Strain Data for 6.2 ft.-lb. Impact of Specimen 1X01620B-4 (25,000 Scans/Sec.)

### 3.3 MOISTURE CONDITIONING

Specimens which were to be moisture conditioned were placed in a humidity chamber which was itself placed in a large thermostatically controlled oven. The humidity chamber was a closed metal cabinet with an internal water bath with forced water circulation over large area wicks. Conditions were checked periodically with wet bulb-dry bulb temperature readings, and the environment confirmed as 88-95% relative humidity and  $160 \pm 5^{\circ}\text{F}$ .

Testing activities were arranged so that all 42 specimens in the program which were to be moisture conditioned were placed in the chamber at one time. Additionally, six weight-gain coupons, each two by three inches in size, taken two each from Panels 1X01619, 0X01620, and 1X01621, accompanied the specimens. These were removed briefly for weighing twice weekly. The moisture content indicated by the weight gain specimens at the conclusion of the exposure ranged from 1.29 to 1.75 percent.

Upon removal from the elevated temperature high humidity environment, the specimens were packaged in sealed polyethylene bags together with moistened absorbent paper and held at room temperature, to be removed only during performance of subsequent testing. All tests were completed within 35 days of the moisture exposure, during which time further moisture diffusion effects at room temperature would be small for intact 16-ply graphite-epoxy laminate. No assessment was made of the moisture pick-up in the impact-damaged specimens.

### 3.4 MOISTURE-TEMPERATURE CYCLING

The moisture-temperature cycling exposure was accomplished by manually transferring the specimens between two environmentally-controlled chambers according to an established schedule. The  $160^{\circ}\text{F}$ -90% nominal RH environment was provided by the humidity chamber described in Section 3.3. The  $-65^{\circ}\text{F}$  environment was obtained with an insulated chamber into which cold nitrogen gas (expanded from a liquid nitrogen supply) was introduced, the demand being established by a thermostat control. The low temperature environment was monitored with thermocouples and held to  $-65^{\circ}\text{F} \pm 5^{\circ}\text{F}$ . Testing schedules within the program were arranged so that all specimens to receive the moisture-temperature cycling

were subjected to the exposure conditions simultaneously. The cyclic environmental exposure shown in Figure 3-8 consists of:

1 hour in 160°F-90% RH environment

30 minutes in -65°F environment

These were applied sequentially, the entire ten cycles of exposure requiring 15 hours elapsed time.

### 3.5 RESIDUAL COLUMN STRENGTH TESTING

Compression testing subsequent to impact and/or environmental exposure was performed using a related set of fixtures which makes it possible to provide various degrees of column support ranging from elastic long column up to fully-restrained ("zero-length") column conditions. The specimen supporting fixtures are designed for use with commercially available MTS hydraulically-actuated grips, which are installed in a standard universal test machine or a MTS test machine.

Installation of a test specimen in the modified hydraulic test grips is shown in Figure 3-9. A close-fitting steel shell surrounds each grip, providing a mount for transverse adjustment screws that prevent destabilizing motion of the fixture and specimen. The grips are rigidly mounted to the base and test head of an MTS 100 kip universal test machine, precise alignment having first been achieved with the aid of spherically-surfaced seats.

Pinned-end column test conditions are provided by two rigid guides or outer platens similar in gross form to those of ASTM 695 (Federal Test Standard 406). On the inner surfaces of the platens are a set of pin-locating platens as shown in Figure 3-10. Five different sets of platens are available. These provide pinned-end test lengths of  $L'=2.38, 1.57, 1.17, 0.78, 0.58$  inches obtained with 3, 5, 7, 11, and 15 bays respectively. Both the seven bay and the eleven-bay pin supports were used in this program. Figure 3-11 shows the assembly of a specimen and the  $L'=0.78$  inch support fixture installed in the test machine.

To confirm the performance of the column test apparatus, a series of tests have been conducted at various pinned-end lengths on a specimen of 0.33 inch

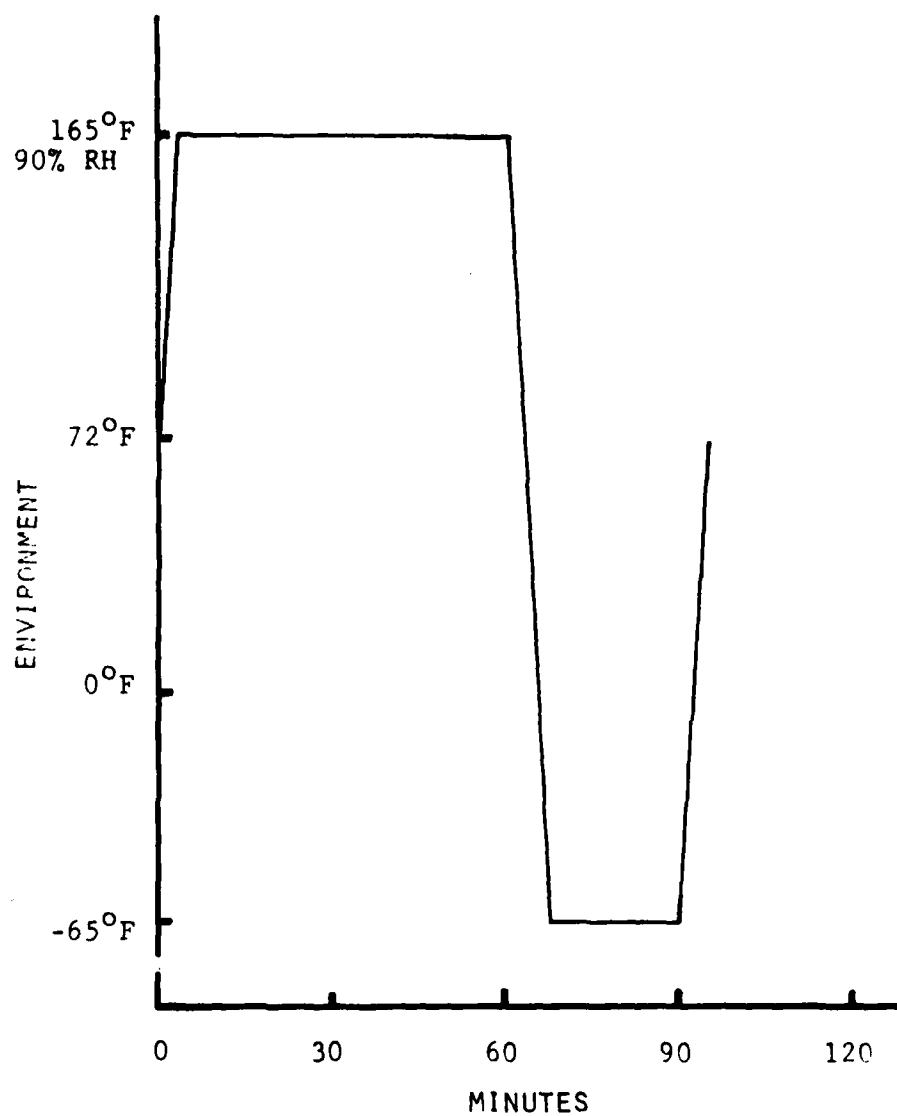


Figure 3-8: Exposure Cycle for Moisture-Temperature Cycling  
(Schematic, rise time approximate)

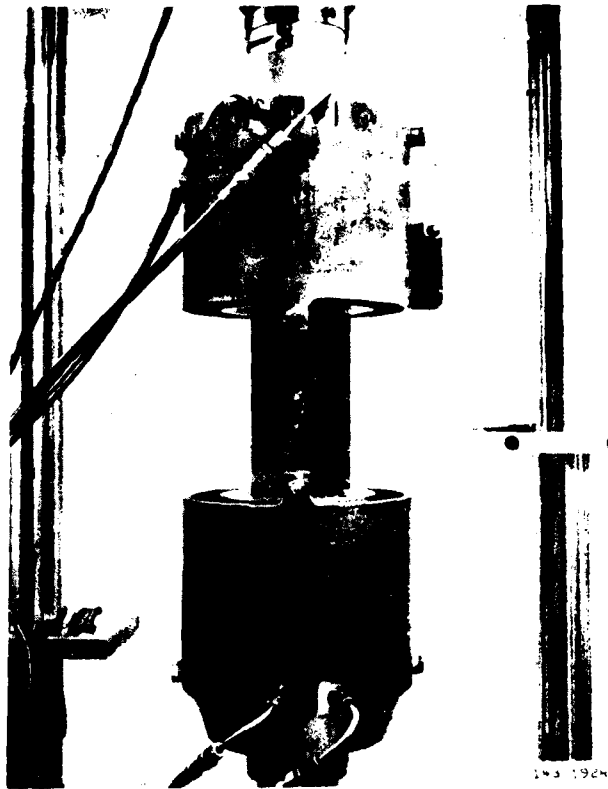


Figure 3-9. Apparatus for Testing 3 x 14-inch Composite Specimens as Plate Columns.



Figure 3-10. Eleven-bay (Ten-pin) Column Restraint Platens, Interior View.

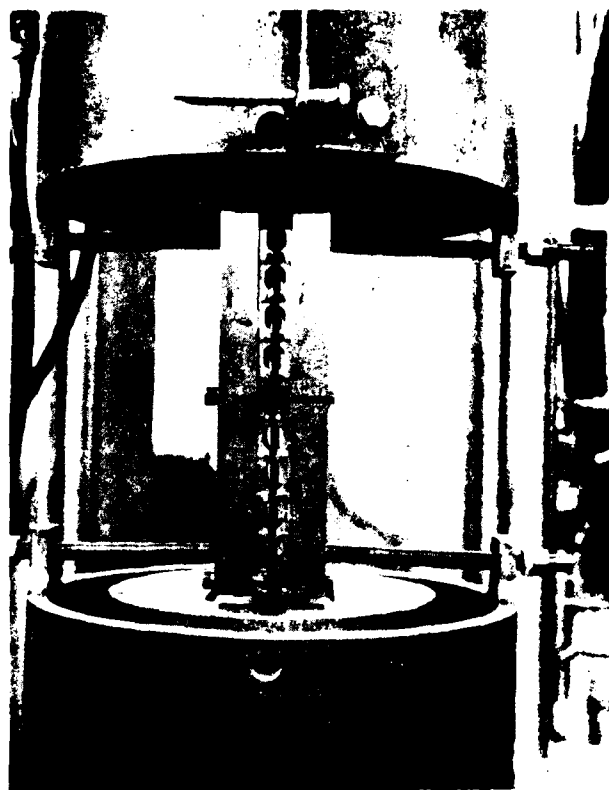


Figure 3-11. Edge View of Specimen Installed in Bernoulli Grip and Supported by Column Restraint Apparatus.

thick, 1.00 inch wide 2024-T3 bare aluminum alloy. Automatically recorded load-deflection curves provided values of the critical load, which, for the shortest test length, proved to be sudden and to involve permanent deformation. The load-deflection data also permitted experimental determination of the modulus of elasticity which was used in constructing the comparison of test data with the Euler relation in Figure 3-12. The regularity and consistency of these data provide confidence in this method of plate-column testing.

Equipment of this type has been used to investigate the effect of environmental exposure on the compression buckling strength of graphite/epoxy laminate. An example of the type of test results obtained is shown in Figure 3-13, which is reproduced from Reference 2.

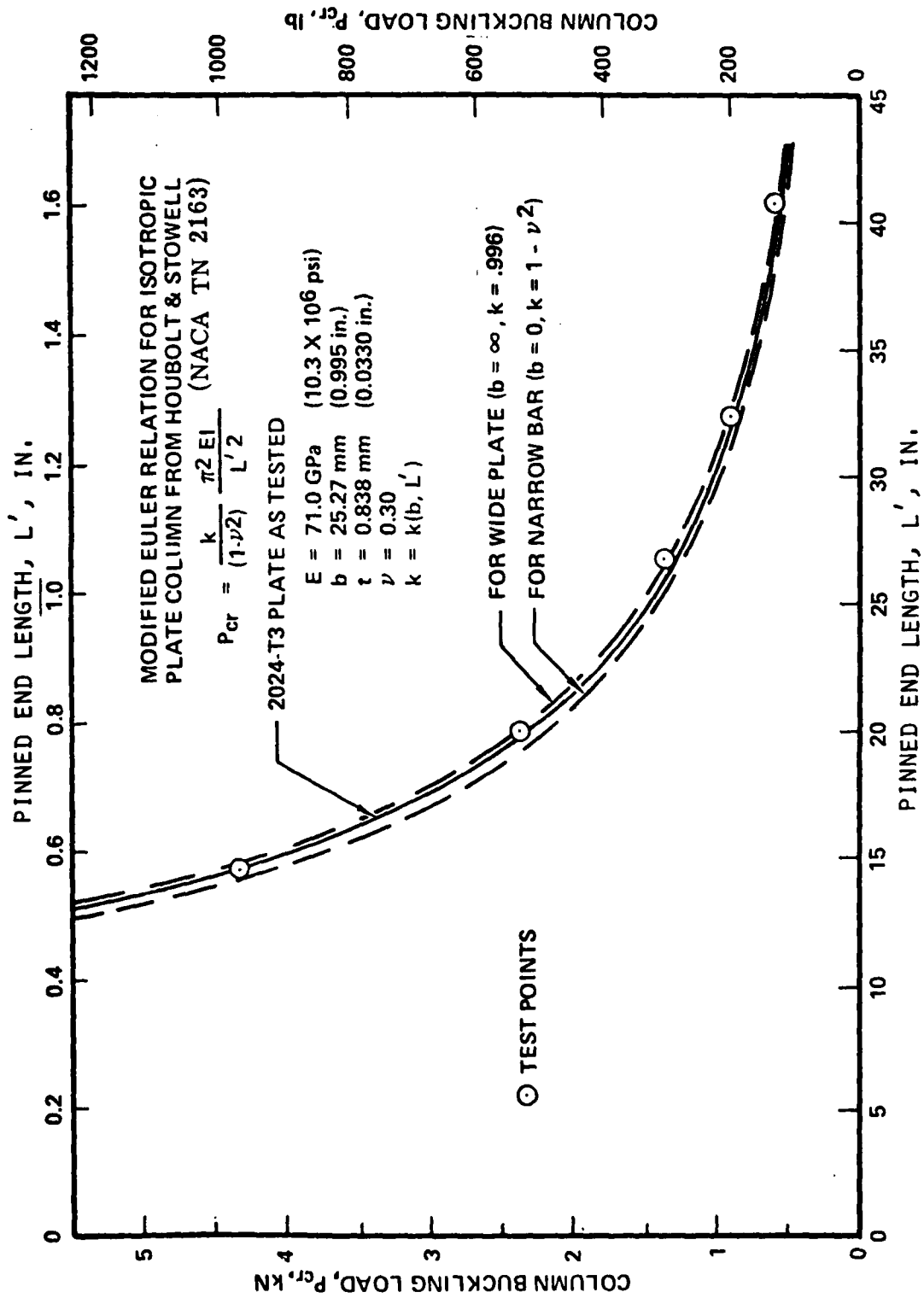


Figure 3-12. Column Test Results Obtained With Aluminum Alloy Specimen.

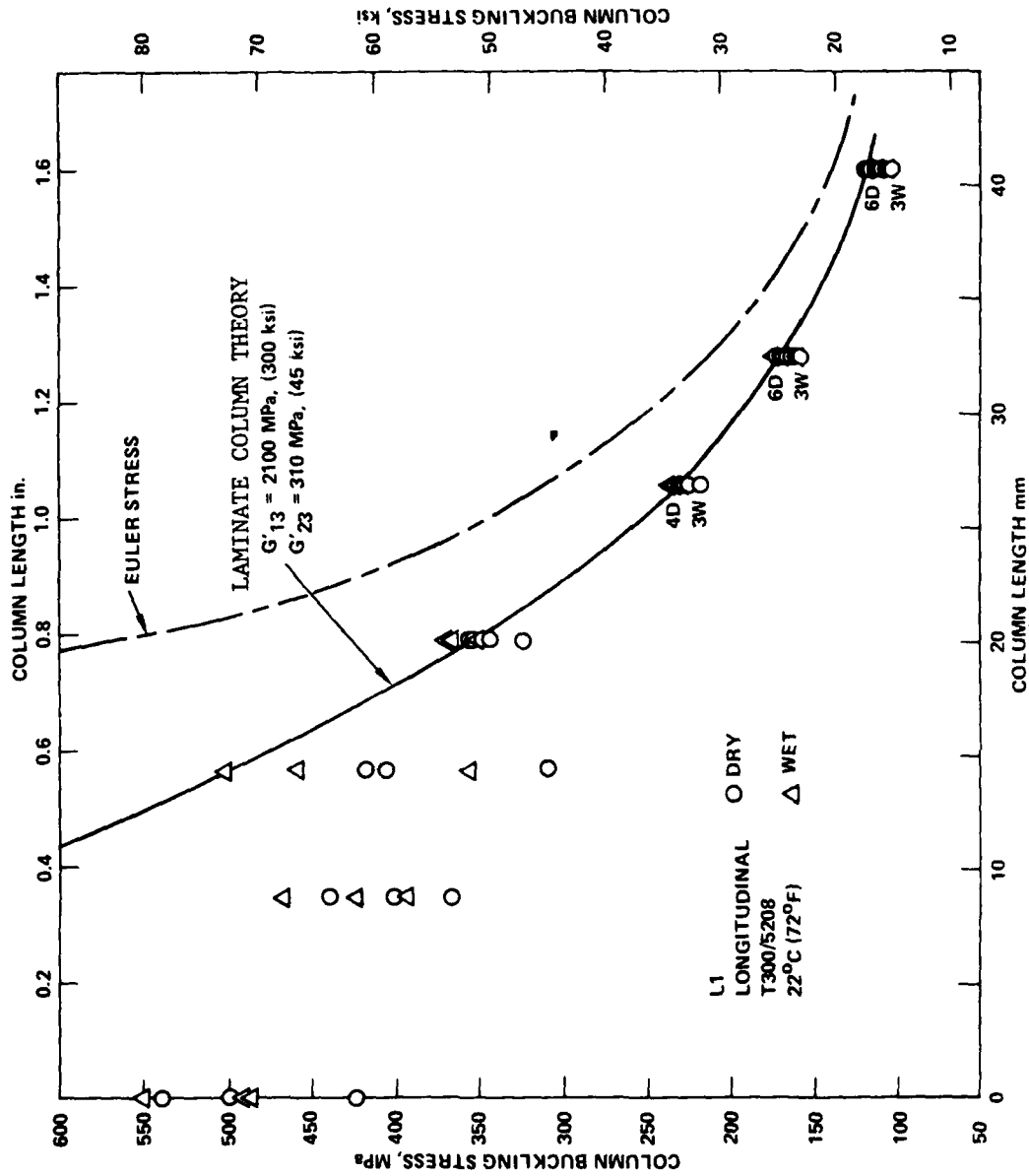


Figure 7-13: Column Test Results at 72°F or T300/5208 16-Ply, Quasi-Isotropic Laminate, from Reference 1.

## SECTION 4

### TEST PROCEDURE

#### 4.1 PRELIMINARY DAMAGE STUDY

A preliminary experimental investigation was made to develop the methods of impact loading and damage assessment required to produce a specific level of impact damage (simulating that caused by an accidentally dropped tool), and to verify that this damage size could be reproduced consistently in replicate specimens. The impact damage level of interest was to be characterized as representing the onset of visible cracking over an area approximately 1.00 to 1.50-inch diameter on one face, to allow direct entrance of moisture into the interior of the laminate.

Two types of supports were evaluated: 1) a rigid frame supporting the specimen along all edges as a simply supported plate with a support width of  $\frac{1}{2}$  inch along the edges and 1 inch along the ends, and 2) a continuous support consisting of a  $\frac{3}{8}$ -inch thick pad of Nomex honeycomb core,  $\frac{3}{16}$ -inch cell size, 4 lb./ft.<sup>3</sup> HRH phenolic paper, arranged to support the entire specimen between end tabs. Results of these preliminary tests are presented in Table 4-1. Typical C-scans and associated B-scans of internal damage as detected by the Holsen ultrasonic system are displayed in Figure 4-1 and 4-2 for the rigid frame and honeycomb core supports, respectively.

Although the internal damage appeared to be of about the same extent whether supported by Nomex honeycomb core or by the rigid frame, the external damage at the rear face was quite different. Slight back surface bulging with minor or no visible cracking was usually obtained with the honeycomb support, as shown in Figures 4-3 and 4-4, and this condition was judged inadequate for the laminar flow type of moisture penetration desired in this program. With the frame support, however, back surface damage involved multiple cracks, the

TABLE 4-1  
PRELIMINARY IMPACT TRIAL RESULTS

SPECIMEN NUMBER	SUPPORT <sup>a</sup> , TYPE	NOMINAL ENERGY Ft-lbs.	VISIBLE <sup>b</sup> DAMAGE	DAMAGE SIZE FROM HOI-SCAN C-SCAN in.
1X01618-1	FR	4.5	1½" Single Crack	1.27 x 0.97
-2	FR	5.1	3 parallel cracks approx. 3" total lgth.	1.5 x 0.93
-3	FR	5.1	¾" x 2" Multiple Cracks	1.5 x 1.12
-4	FR	5.1	¾" x 1" Multiple Cracks	1.45 x 1.11
-5	FR	4.5	1½" x 1/8" 4 cracks	1.25 x 1.15
-6	FR	4.5	1½" x ¾" Multiple Cracks	
-7	H/C	4.6	Minor approx. ½" - 2 cracks + out of plane bulge	1.38 x 1.28
-8	H/C	4.6	" " "	1.35 x 1.30
-9	H/C	4.6	" " "	
-10	H/C	5.2	" " "	1.26 x 1.25
-11	H/C	5.2	" " "	1.32 x 1.35
-12	H/C	5.2	" " "	1.34 x 1.26
-13	H/C	5.6	¾" x 3/4" bulge slightly greater than above	1.45 x 1.37
-14	H/C	5.6	¾" single crack	1.35 x 1.34
-15	H/C	6.0	Approx. 4 cracks 1" total	1.41 x 1.34
-16	H/C	6.0	Approx. 4 cracks 1" total	1.42 x 1.37
-17	H/C	4.6	Minor visible damage approx. ¾" horizontal crack & approx. 1" along fiber (weight hit twice)	1.38 x 1.30
-18	FR	4.0	No visible damage	Not Scanned
-19	FR	3.4	No visible damage	Not Scanned
-20	FR	4.5	Approx. 1" cracks along fibers only	1.04 x 1.26
-21 <sup>c</sup>	FR	5.6	Slightly more damage than #24 below	2.48 x 1.62
-22 <sup>c</sup>	FR	6.2	Slightly more damage than #24 below	Not Scanned
-23 <sup>c</sup>	FR	5.6	No visible damage	2.57 x 1.62
-24 <sup>c</sup>	FR	6.7	Minor visible damage approx. 1" horizontal crack & approx. 1" along fiber	2.55 x 1.62

a = FR-rigid frame, with ½" width along specimen edges, 1" width at ends, H/C-nonax  
honeycomb core

b = Damage measured parallel and perpendicular to fiber direction

c = Spec. cut from panel to transverse direction



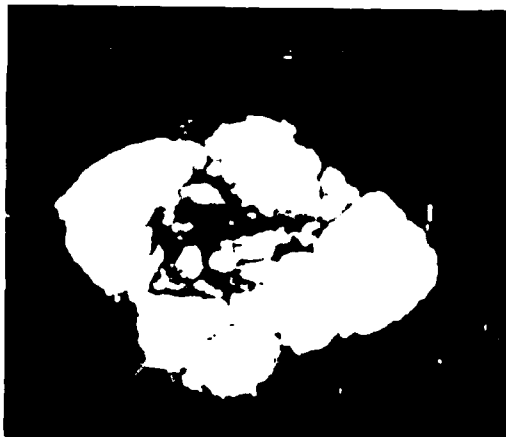
C-Scan of TX01618-5

5.1 ft. x 1.5 in. x 1.1 in.



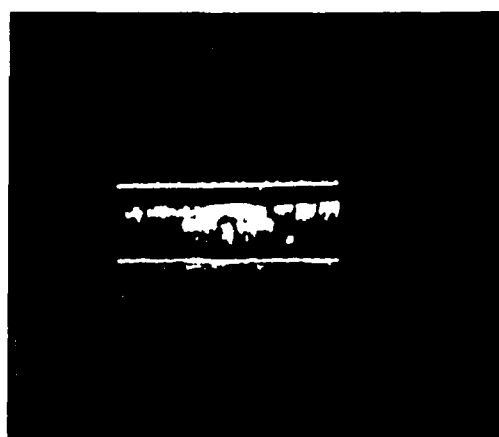
B-Scan of TX01618-5

5.1 ft. x 1.5 in. x 1.1 in.



C-Scan of TX1618-3

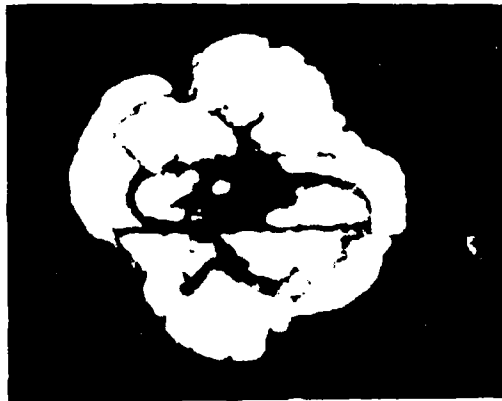
5.1 ft. x 1.5 in. x 1.1 in.



B-Scan of TX1618-3

5.1 ft. x 1.5 in. x 1.1 in.

Figure 4-1: Typical Ultrasonic C-Scan & B-Scan of Polyurethane Ultrathin Polyurethane Impact Coating (PUC) on a steel plate.



C-Scan IX01618-8

100-100, 1.0, 1.0, 1.0, 1.0, 1.0



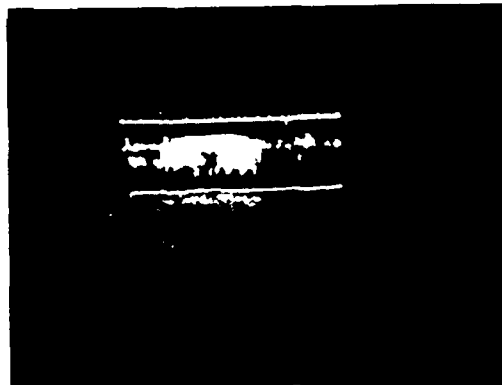
B-Scan IX01618-8

100-100, 1.0, 1.0, 1.0, 1.0, 1.0



C-Scan IX01618-8

100-100, 1.0, 1.0, 1.0, 1.0, 1.0



B-Scan IX01618-8

100-100, 1.0, 1.0, 1.0, 1.0, 1.0

Figure 4-2: The figure shows the results of the C-Scan and B-Scan of the IX01618-8. The C-Scan shows a complex, irregular shape with a central dark region and a lighter, textured outer boundary. The B-Scan shows a horizontal, elongated shape with a central dark region and a lighter, textured outer boundary.

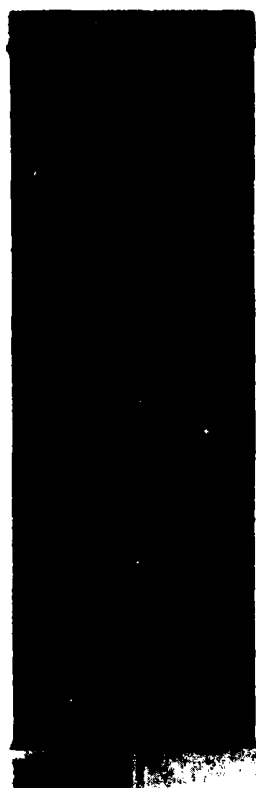


Figure 7-3: Back Surface of Specimen 15018-15 After Inspection. Honeycomb is Barely Visible.

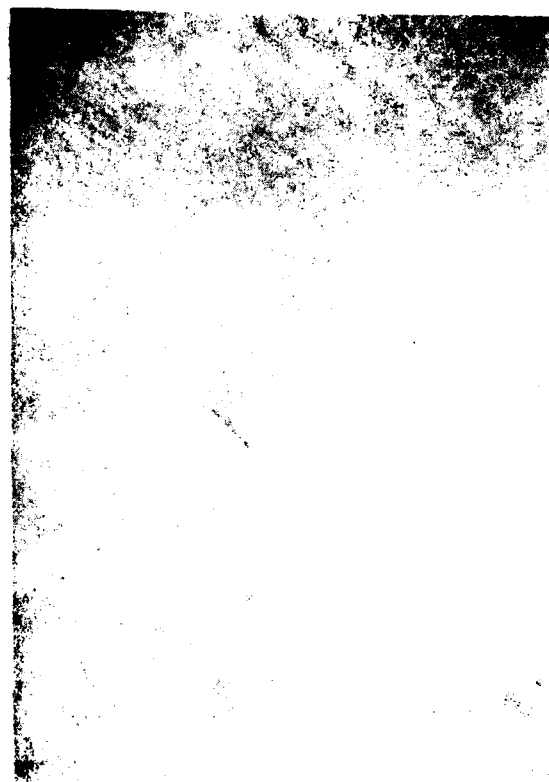


Figure 4-4: A black and white photograph of a rock face showing a dark, irregular shape in the center, possibly a shadow or a specific feature on the surface.

extent of which could be controlled by the height of the drop. A photograph of typical back-surface damage obtained with this support is presented as Figure 4-5. The cracks and separation have been highlighted with chalk dust to make them more apparent in the photograph; they were, however, barely visible to the naked eye.

As a result of the preliminary experimental investigation the following conditions were found to produce the type and amount of damage desired and were established for the remainder of the program:

Impactor:	Steel rod 1.00 in. diam. x 12 in. long Spherical nose 1.00 in. diam. Mass: 2.62 lb.
Height of drop:	28.19 inches
Velocity at impact:	12.2 ft./sec. (nominal)
Energy at impact:	6.15 ft.-lb. (nominal)
Specimen support:	Frame, under side only; 0.50 in. wide at long edges, 1.00 in. wide at ends, bearing on tabs. Central 2.00 x 11.75 inches unsupported.

This provided slightly more back-surface damage than shown in Figure 4-5. Internal damage consistently approximated that shown in Figure 3-4.

Because of frictional effects and windage, the actual velocity of the impactor was always somewhat lower than the nominal value calculated from the height of drop. The mean value of the velocity at impact, as measured from high speed motion picture records taken of each test, was 11.9 fps, with a probable error of  $\pm 0.2$  fps. Consequently the energy at impact was about 5.76 ft.-lb. with a probable error of  $\pm 0.20$  ft.-lb.

#### 4.2 MAIN PROGRAM TEST PROCEDURES

The main program of exposure and test is outlined in Table 4.2. The program required twelve groups of six specimens each, each group subjected to a different combination of impact and exposure. Five of the specimens of each group were then tested in column compression; the sixth was sectioned for micrographic study. In addition, a thirteenth group of five specimens which had not been



Figure 4-12. Close-up of the central part of the specimen, showing the texture and the central feature.

TABLE 4-2  
PROGRAM OUTLINE

Group	Test Conditions	Residual Compression Strength Tests
A	<u>IMPACT EFFECT AND INTERACTION WITH MOISTURE AND LOW TEMPERATURE</u>	
A1	Impact <sup>1</sup> , (R.T. - dry)	R. T., dry
A2	Impact <sup>1</sup> , moisture condition <sup>2</sup>	R. T., moisture content of 1.0%
A3	Impact <sup>1</sup> , moisture condition <sup>2</sup> , low temperature exposure <sup>3</sup>	R. T., moisture content of 1.0%
A4	Impact <sup>1</sup> , 10 cycles (moisture condition alternated with low temperature exposure <sup>4</sup> )	R. T., moisture content of 1.0%
B	<u>MOISTURE EFFECT AND INTERACTION WITH LOW LEVEL IMPACT AND LOW TEMPERATURE</u>	
B1	Moisture condition <sup>2</sup>	R.T., moisture content of 1.0%
B2	Moisture condition <sup>2</sup> , impact <sup>1</sup>	R. T., moisture content of 1.0%
B3	Moisture condition <sup>2</sup> , impact <sup>1</sup> , low temperature exposure <sup>3</sup>	R. T., moisture content of 1.0%
B4	Moisture condition <sup>2</sup> , impact <sup>1</sup> , 10 cycles (moisture condition alternated with low temperature exposure <sup>4</sup> )	R. T., moisture content of 1.0%
C	<u>LOW TEMPERATURE EFFECT AND INTERACTION WITH LOW LEVEL IMPACT AND MOISTURE</u>	
C1	Low temperature exposure <sup>3</sup>	R. T., dry
C2	Low temperature exposure <sup>3</sup> , impact <sup>1</sup>	R. T., dry
C3	Low temperature exposure <sup>3</sup> , impact <sup>1</sup> , moisture condition <sup>2</sup>	R. T., moisture content of 1.0%
C4	Low temperature exposure <sup>3</sup> , impact <sup>1</sup> , moisture condition <sup>2</sup> , 10 cycles (moisture condition alternated with low temperature exposure <sup>4</sup> )	R. T., moisture content of 1.0%
D1	AS FABRICATED	R. T., dry

<sup>1</sup> "C" Scan before and after impact.

<sup>2</sup> Moisture Condition - exposure to 160°F and 95% R.H. with gain of 1.0% by weight.

<sup>3</sup> Low Temperature Exposure - exposure to -65°F for ½ hour.

<sup>4</sup> 160°F, 95% R.H. for 1 hour, cool down to -65°F, hold ½ hour, and repeat ten times.

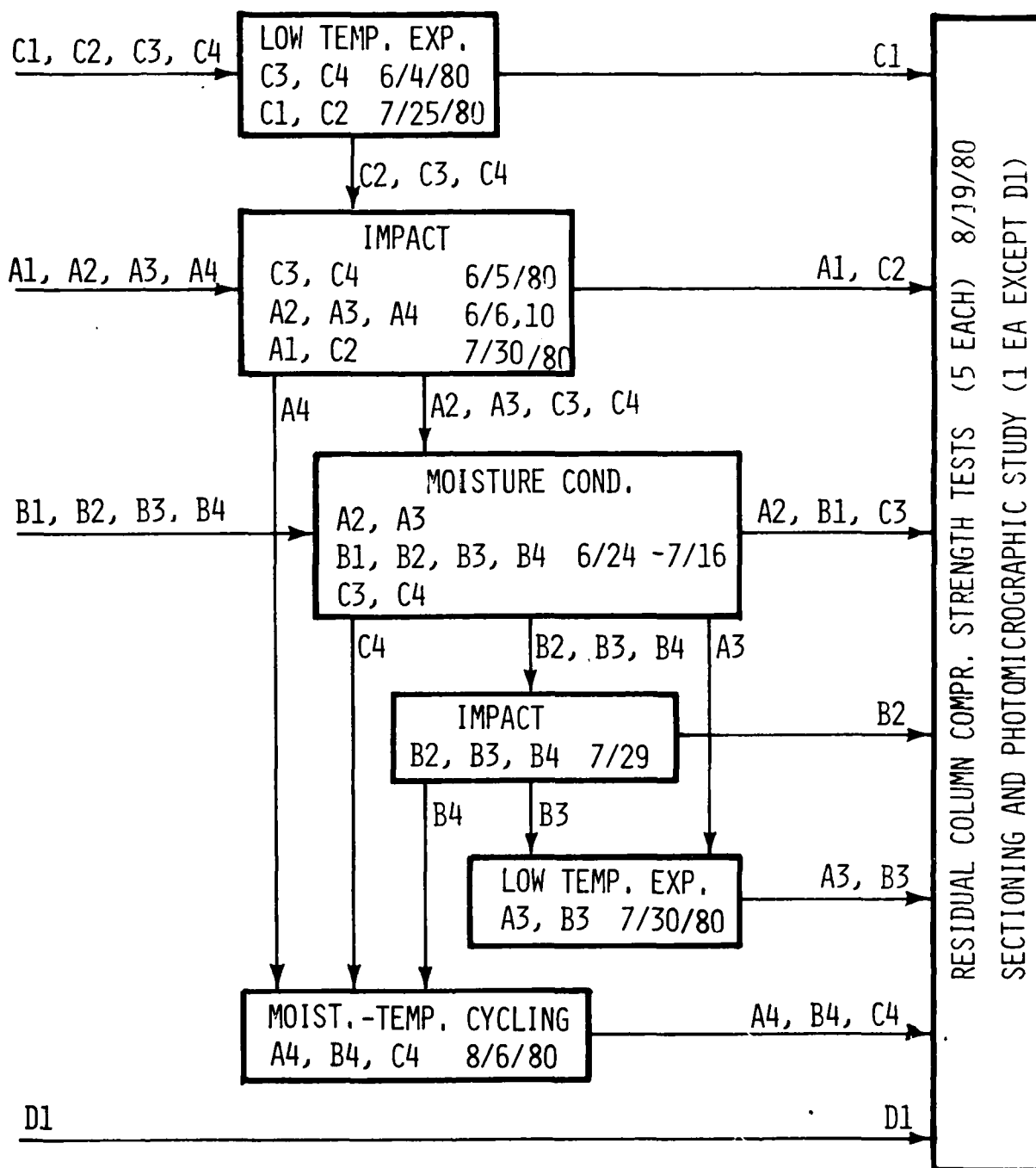
NOTE: Five specimens as above in each group.

All groups except D1 also included a sixth specimen for micrographic study.

subjected to any previous exposure of impact loading was tested in column compression to establish a baseline value for comparison. A sequence of testing and exposure was arranged that would perform the program efficiently and also in a manner which would minimize between-group variations. Figure 4-6 is a flow chart which identifies the sequence of operations. The dates shown in Figure 4-6 for tests of specimens in groups A1, C1 and C2 are those for the second, replacement series.

The first tests to be completed in the program were those on the original specimens comprising groups A1, C1, and C2, and the residual column strength tests on these specimens were performed with a pinned-end column length of  $L'=1.17$  inches. This spacing was selected in order that the major portion of the typical damaged area would fall between pin-supports. However, for the laminate under test, tests at this pinned-end length produced elastic column failure. The affect of damage on buckling phenomena is less important in the elastic region than it is at higher stresses, and in this case the presence of damage resulted in only about six percent reduction in average column strength.

In order to obtain a residual strength determination which was more sensitive to the presence of damage, it was decided to conduct residual column strength tests at a pinned-end length of 0.78-inch instead of 1.17-inches. This changed the mode of column failure from the elastic, intermediate length regime to the inelastic, short column length range, and resulted in a substantial increase in sensitivity to impact damage. All subsequent residual column strength tests were conducted at  $L'=0.78$ -inch.



SIX SPECIMENS IN EACH GROUP EXCEPT FIVE IN D1

FIGURE 4-6. TEST PROGRAM FLOW CHART

## SECTION 5

## TEST RESULTS

5.1 RESULTS OF MECHANICAL TESTS

Test data compiled in the course of the program are presented in Table 5-1. To facilitate assessment of exposure effects and interaction effects, the mean values of the test results obtained for each of the different groups are compared in Table 5-2. These tabulations include the energy deposited in the specimen at impact (impact energy less rebound energy), the "area" of impact damage (width times length dimensions shown in C-scan), and residual column compression strength. A plot of the residual strength data is presented in Figure 5-1, in a form which permits comparison of the results with different environmental exposures.

The scatter of individual test data, expressed by the coefficient of variation, is of the order of five percent. When using only five replicate specimens, differences between the mean values must be more than twice as large as the coefficient of variation to be considered significant to a 90 percent confidence level. No differences this large are found between the mean values in Table 5-2, except when comparing impact-damaged specimens with those not impacted at all. The immediate results of the test program, therefore, are that **these** specific environmental exposures and sequences of exposures have no significant effect on impact damage or on residual compressive strength after impact. This conclusion is graphically evident in Figure 5-1. Here it is seen that, for each of the three conditions of exposure prior to impact, the impact damage reduces the residual compressive strength, but environmental exposure subsequent to impact causes no further reduction.

The data do provide additional indications, however, which may lead to tentative conclusions.

TABLE 5-1  
RESULTS OF IMPACT, EXPOSURE, AND RESIDUAL STRENGTH TESTS

Group	Impact and Exposure Sequence	Specimen			Impact Data		Residual Column Strength				
		ID	Width (in.)	Avg. Thick. (in.)	Impact Velocity (fps)	Rebound Velocity (fps)	Energy Deposited (ft.-lb.)	Damage Area (sq. in.)	Failure L=0.78 (ksi)	Stress L=1.17 (ksi)	Failure Location
A1	Impact only	19A-10	2.989	0.0931	11.7	8.4	2.70	1.08x1.45		32.9	Central
		19B-7	2.985	0.0942	11.6	8.5	2.53	1.11x1.69		32.7	"
		20B-5	2.989	0.0935	11.7	8.4	2.70	1.21x1.56		33.3	"
		21C-4	2.988	0.0891	11.8	8.4	2.79	1.10x1.57		30.6	"
		21C-8	2.989	0.0888	11.7	8.6	2.56	1.01x1.62		30.9	"
		74-3	3.000	0.0916	12.0	9.4	2.26	(2)	42.8		Central
		74-8	2.999	0.0921	12.3	9.4	2.56	(2)	36.1		"
		74-14	2.999	0.0901	11.9	9.1	2.39	(2)	39.4		"
A2	Impact; moisture	74-18	3.001	0.0904	12.2	8.6	3.05	(2)	37.8		"
		74-19	3.001	0.0922	11.9	8.9	2.54	(2)	38.9		"
		74-15	2.999	0.0892	12.2	8.6	3.05	(2)	(3)		"
		19B-10	2.989	0.0942	11.6	8.7	2.40	1.17x1.37	39.4		Central
		19C-9	2.989	0.0923	11.9	7.9	3.22	1.19x1.47	35.3		"
		20B-4	2.988	0.0933	11.9	8.7	2.68	0.98x1.70	39.8		"
		21A-3	2.988	0.0899	11.6	8.3	2.67	1.01x1.73	41.0		"
		21C-1	2.987	0.0874	11.8	8.8	2.51	1.07x1.53	39.6		"
A3	Impact; moisture; low temperature	20A-7	2.986	0.0912	12.0	8.6	2.85	0.98x1.66	(3)		"
		19B-9	2.988	0.0937	11.8	8.1	3.00	1.06x1.75	37.7		Central
		20C-2	2.989	0.0910	11.9	8.4	2.89	1.00x1.80	39.0		"
		20C-7	2.986	0.0916	11.7	8.6	2.56	1.10x1.67	39.1		"
		21B-10	2.989	0.0897	12.1	8.6	2.95	1.06x1.72	35.6		"
		21C-2	2.987	0.0878	11.9	8.5	2.82	1.08x1.54	39.3		"
		19A-9	2.989	0.0932	11.6	8.7	2.40	0.98x1.74	(3)		"

Continued on next page

(1) Data lost due to instrumentation.

(2) Data not taken.

(3) Specimen sectioned for photomicrography.

TABLE 5-1 (Continued)  
RESULTS OF IMPACT, EXPOSURE, AND RESIDUAL STRENGTH TESTS

Group	Impact and Exposure Sequence	Specimen			Impact Data			Residual Column Strength			
		ID	Width (in.)	Avg. Thick. (in.)	Impact Velocity (fps)	Rebound Velocity (fps)	Energy Deposited (ft.-lb.)	Damage Area (in. x in.)	Failure Stress L <sup>1</sup> =1.17 (ksi)	Failure Bay Location	
A4	Impact; moisture-temp. cycling	19C-3	2.988	0.0929	11.8	8.5	2.73	1.07x1.53	40.0	Central	
		19C-8	2.989	0.0924	11.8	8.6	2.66	1.08x1.61	39.5	"	
		20C-4	2.989	0.0918	11.8	8.6	2.66	0.78x1.33	39.7	"	
		20C-10	2.988	0.0919	12.0	8.6	2.85	1.03x1.50	39.9	"	
		21B-2	2.989	0.0903	11.7	8.2	2.83	0.92x1.53	42.8	"	
		21A-4	2.988	0.0999	11.7	8.4	2.87	1.07x1.66	(3)	"	
B1	Moisture conditioned only	19C-1	2.987	0.0929	This group not subject to impact					41.8	End
		20C-3	2.989	0.0914						51.8	"
		20C-9	2.989	0.0910						50.2	"
		21B-4	2.989	0.0905						49.5	"
		21C-5	2.988	0.0900						50.0	"
		19A-2	2.988	0.0929						(3)	"
B2	Moisture; impact	19A-7	2.986	0.0936	12.3	8.5	3.22	(2)	44.7	Central	
		19C-10	2.989	0.0928	12.2	8.6	3.05	(2)	42.9	Intermediate	
		20B-9	2.989	0.0917	12.0	9.1	2.49	(2)	45.4	Central	
		21A-2	2.988	0.0902	12.2	8.6	3.05	(2)	41.0	"	
		21A-7	2.988	0.0901	12.2	8.5	3.12	(2)	40.9	"	
		20C-1	2.989	0.0914	12.3	8.7	3.08	(2)	(3)	"	
B3	Moisture; impact; low temperature	19B-4	2.989	0.0944	12.1	8.4	3.09	(2)	45.2	Central	
		19B-6	2.989	0.0947	11.9	8.7	2.68	(2)	42.7	"	
		20C-5	2.989	0.0923	12.2	9.0	2.76	(2)	44.9	"	
		20A-10	2.989	0.0908	12.0	9.0	2.56	(2)	41.3	"	
		21B-7	2.986	0.0916	12.2	8.6	3.05	(2)	45.0	"	
		21C-6	2.988	0.0922	11.9	8.9	2.54	(2)	(3)	"	

Continued on next page

(1) Data lost due to instrumentation.

(2) Data not taken.

(3) Specimen sectioned for photomicrography.

TABLE 5-1 (Continued)  
RESULTS OF IMPACT, EXPOSURE, AND RESIDUAL STRENGTH TESTS

Group	Impact and Exposure Sequence	Specimen			Impact Data			Residual Column Strength			
		ID	Width (in.)	Avg. Thick. (in.)	Impact Velocity (fps)	Rebound Velocity (fps)	Energy Deposited (ft.-lb.)	Damage Area (sq. in.)	Failure Stress L'=0.78 (ksi)	Failure Bay Location	
B4	Moisture; impact; moist.-temp. cycling	19A-5	2.987	0.0937	12.4	8.5	3.32	(2)	42.2	Central	
		19C-4	2.988	0.0923	12.0	8.6	2.85	(2)	42.5	"	
		20B-3	2.989	0.0927	12.3	8.6	3.15	(2)	42.6	"	
		21C-3	2.988	0.0881	12.2	8.3	3.25	(2)	42.9	"	
		21C-10	2.989	0.0885	12.2	8.9	2.83	(2)	40.5	"	
		20B-6	2.989	0.0932	12.2	9.1	2.69	(2)	(3)	"	
C1	Low temp. exposure only	19B-5	2.988	0.0950					34.3	Intermediate	
		20A-8	2.989	0.0903					33.7	End	
		20B-10	2.989	0.0926					35.0	Intermediate	
		21A-8	2.989	0.0895					34.0	End	
		21B-8	2.989	0.0904					33.7	"	
		74-4	3.002	0.0904	This group not subject to impact					34.3	End
		74-5	3.000	0.0906						46.7	End
		74-9	2.998	0.0906						53.6	Intermediate
C2	Low temp.; impact	74-16	3.000	0.0908					51.4	End	
		74-20	3.001	0.0907					45.0	End	
		74-17	2.999	0.0877					(3)	"	
		19A-4	2.987	0.0936	(1)	(1)		1.07x1.37	32.2	Central	
		19C-7	2.986	0.0926	10.5	7.3	2.32	1.12x1.62	30.7	"	
		20B-8	2.989	0.0920	11.5	7.9	2.84	1.04x1.48	32.4	"	
		21A-6	2.988	0.0910	(1)	(1)		(2)	32.7	"	
21C-7	2.985	0.0896	12.1	8.5	3.02	1.08x1.38	32.5	"			

Continued on next page

(1) Data lost due to instrumentation.

(2) Data not taken.

(3) Specimen sectioned for photomicrography.

TABLE 5-1 (Continued)  
RESULTS OF IMPACT, EXPOSURE, AND RESIDUAL STRENGTH TESTS

Group	Impact and Exposure Sequence	Specimen		Impact Data		Energy Deposited (ft.-lb.)	Damage Area (sq. in.)	Residual Column Strength		Failure Bay Location
		ID	Width (in.)	Avg. Thick. (in.)	Impact Velocity (fps)	Rebound Velocity (fps)		Failure Stress L <sup>1</sup> -0.78 (ksi)	Stress L <sup>1</sup> -1.17 (ksi)	
C2	Low temp.; impact	74-1	3.001	0.0904	12.3	9.6	2.41	38.7		Central
		74-2	3.001	0.0909	12.3	9.0	2.86	39.7		"
		74-10	2.998	0.0889	12.0	9.7	2.03	38.5		"
		74-12	2.999	0.0909	11.9	9.6	2.01	38.0		"
		74-13	3.000	0.0908	12.0	9.2	2.41	41.3		"
		74-11	3.000	0.0899	11.0	8.2	2.19	(3)		"
C3	Low temp.; impact; moisture	19B-2	2.982	0.0932	11.9	8.7	2.68	37.0		Central
		19C-5	2.988	0.0931	12.0	8.2	3.12	37.4		"
		20A-5	2.988	0.0920	11.7	8.4	2.70	40.7		"
		21A-10	2.989	0.0887	11.5	8.2	2.64	38.7		"
		21B-9	2.989	0.0900	(1)	(1)		42.4		End
		20A-3	2.988	0.0907	11.6	8.4	2.60	(3)		
C4	Low temp.; impact; moist.-temp. cyl.	19A-3	2.987	0.0934	11.7	8.6	2.56	39.8		Central
		20B-1	2.988	0.0923	11.9	8.4	2.89	42.8		"
		20C-6	2.988	0.0922	11.8	8.7	2.59	40.3		"
		21B-1	2.988	0.0898	11.8	8.3	2.86	45.7		"
		21B-6	2.976	0.0921	11.6	8.4	2.60	42.1		"
		19B-1	2.987	0.0942	11.8	8.5	2.73	(3)		"
D1	None (column test as fabricated)	19A-1	2.988	0.0945				44.6		Intermediate End
		20A-1	2.988	0.0923				50.0		End
		21A-1	2.981	0.0908	This group not subject to impact					Intermediate End
		74-6	2.998	0.0904				41.5		Intermediate End
		74-7	2.999	0.0948				41.2		End

(1) Data lost due to instrumentation.

(2) Data not taken.

(3) Specimen sectioned for photomicrography.

TABLE 5-2  
MEAN VALUES OF TEST RESULTS

Group	Impact and Exposure	Energy (1) Deposited (ft.-lb.)	Damage Area (in. <sup>2</sup> )	Residual Column Strength (ksi)	(1)
A1 Original Replacement	Impact only	2.66 + .07 2.65 + .23	1.74 + .10 (2)	39.0 + 1.7	---
A2	Impact, Moisture	2.72 + .20	1.67 + .04	39.0 + 1.5	
A3	Impact; Moisture; Low Temp.	2.77 + .16	1.77 + .05	38.1 + 1.0	
A4	Impact; Moist.-Temp. Cycling	2.77 + .07	1.54 + .19	40.4 + 0.9	
B1	Moisture only	---	---	48.7 + 2.7	
B2	Moisture; Impact	3.00 + .18	(2)	43.0 + 1.4	
B3	Moist.; Impact; Low Temp.	2.78 + .16	(2)	43.8 + 1.2	
B4	Moist.; Impact; Moist.-Temp. Cyl.	3.01 + .18	(2)	42.7 + 0.7	
C1 Original Replacement	Low Temp. Only	---	---	46.2 + 5.1	---
C2 Original Replacement	Low Temp.; Impact	2.73 + .24 2.32 + .22	1.58 + .11 (2)	39.1 + 0.9	---
C3	Low Temp.; Impact; Moisture	2.75 + .14	1.50 + .17	39.2 + 1.6	
C4	Low Temp; Impact; Moist. Temp. Cyl.	2.71 + .10	1.68 + .07	42.1 + 1.6	
D1	No Env. Exposure or Impact	---	---	44.4 + 2.4	

(1) Mean + probable (+ 0.68σ) error

(2) Data not taken

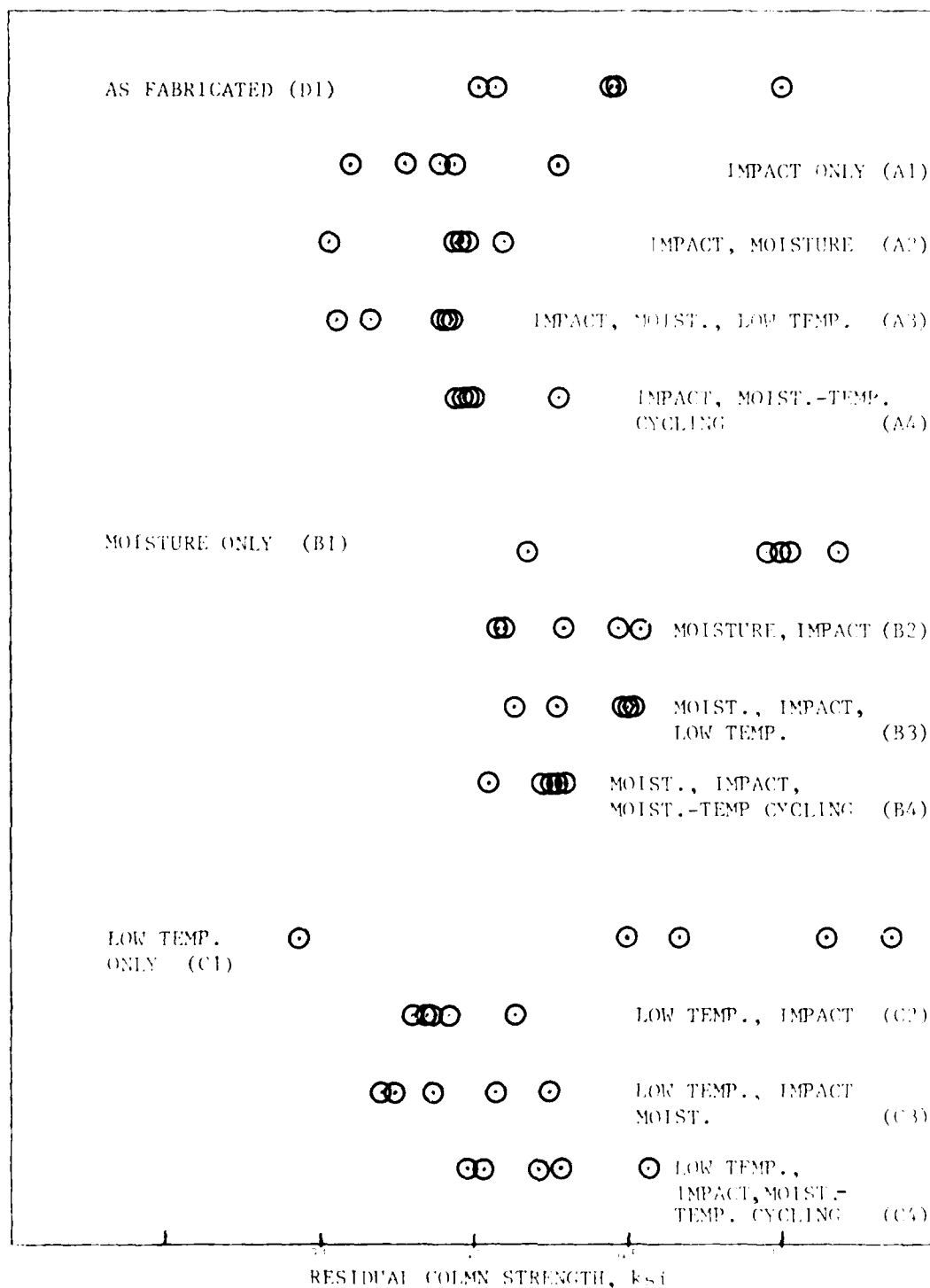


Figure 5-1: Results of Residual Column Strength Tests.

#### 5.1.1 Effect of Moisture Conditioning on Impact Damage

Comparison of the mean values of the net energy absorbed under impact by the specimens of different groups, Table 5-2, indicates that moisture-conditioned material may be a better energy absorber than "dry" or as-fabricated laminate. While this indication does not necessarily mean that moisture conditioning improves the resistance to impact damage, such a conclusion is suggested by the data distributions of Figure 5-1 and supported by the mean values of residual column strength in Table 5-2. Comparison of these data for groups A1, A2, A3, A4, C2 and C3 with groups B2, B3 and B4, indicates that when specimens are moisture conditioned prior to impact, the residual column strength is 6 to 15 percent higher than when moisture conditioning is delayed until after impact, or when moisture conditioning is omitted entirely.

Because this indication is based on several different sets of comparisons rather than just one, the statistical significance is stronger than suggested above. An estimate may be made by combining the comparisons after normalizing the data in each set with respect to a reference level which accounts for differences between the sets. An analysis of this type, comparing residual strength of groups A2, A3 and A4 with B2, B3 and B4, is presented in Table 5-3, the normalizing factor for each set being the mean of the strengths for the groups which were dry when subject to impact. Though the distribution of test data may not be normal and the analysis is only approximate, the statistical inference, that moisture improves the resistance to impact, is strong.

#### 5.1.2 Effect of Low Temperature Exposure

The product of the damage dimensions seen in the C-scan records provides a more convenient and more consistent measure of internal impact damage than either width or length taken alone. Comparison of the means of this product value for the various groups, as listed in Table 5-2, indicates no significant difference in the extent of damage as a result of exposure to low temperature. Comparison of the means of the residual strength data of group C1 with D1, C2 with A1, C3 with A2, and C4 with A3, indicates no significant differences in the residual column strength as a result of low temperature exposure prior to impact.

TABLE 5-3  
APPROXIMATE STATISTICAL ANALYSIS FOR EFFECT OF  
MOISTURE CONDITIONING ON RESIDUAL STRENGTH

Normalizing Basis	Group	Specimen	Normalized Residual Strength	Group	Specimen	Normalized Residual Strength
$\bar{X}_{A2}=39.0$	A2	19B-10	1.01	B2	19A-7	1.15
		19C-9	0.91		19C-10	1.10
		20B-4	1.02		20B-9	1.16
		21A-3	1.05		21A-2	1.05
		21C-1	1.02		21A-7	1.05
$\bar{X}_{A3}=38.1$	A3	19B-9	0.99	B3	19B-4	1.19
		20C-2	1.02		19B-6	1.12
		20C-7	1.03		20C-5	1.18
		21B-10	0.93		20A-10	1.08
		21C-2	1.03		21B-7	1.18
$\bar{X}_{A4}=40.4$	A4	19C-3	0.99	B4	19A-5	1.04
		18C-8	.98		19C-4	1.05
		20C-4	.98		20B-3	1.05
		20C-10	.99		21C-3	1.06
		21B-2	1.06		21C-10	1.00
			$\bar{X}_A = 1.000$	$\bar{X}_B = 1.097$		
			$s_A = 0.045$	$s_B = 0.061$		
			$N_A = 15$	$N_B = 15$		
<u>Analysis (Ref. 3)</u>						
Hypothesis: $\bar{X}_B \leq \bar{X}_A$ ; reject if $t < t_{1-.99, df}$						
$t = (\bar{X}_A - \bar{X}_B) / s_p \sqrt{(1/N_A) + (1/N_B)} = -4.788$						
$s_p^2 = [N_1 - 1)s_A^2 + (N_2 - 1)s_B^2] / (N_A + N_B - 2) = 0.054$						
$df = (N_A + N_B - 2) = 28$						
$t_{0.01, 43} = -2.467$						
Conc: $\bar{X}_B > \bar{X}_A$ ; that is, mean residual strength of specimens moisture-conditioned prior to impact exceeds that of dry specimens, to better than 99% confidence level						

### 5.1.3 Effect of Moisture-Temperature Cycling

The question of whether freeze-thaw cycling increased the internal damage caused by impact is answered by comparing mean values of residual strength (Table 5-2) of groups A3 with A4, B3 with B4, and C3 with C4. In two of these cases the mean values of residual strength were higher for moisture-temperature cycled specimens. However, none of the differences can be termed significant.

### 5.1.4 Maximum Force at Impact

Strain gage data interpreted by means of static calibration to indicate force at impact were obtained in 18 of the 60 scheduled impact tests. The average of these indicated a peak force of 639 lb. with a probable error of  $\pm 92$  lb. The scatter of this measurement was much larger than the variation in the test impact velocity and no differences could be attributed to environmental exposure conditions.

## 5.2 PHOTOMICROGRAPHIC EXAMINATIONS

The specimens selected for micrographic examination were sectioned transversely 0.25-inch from the impact point, mounted in epoxy to support the damaged region, then ground back to the impact station and polished. The two specimens which had been subjected to environmental exposure only, without impact, were sectioned centrally and polished. Photomicrographs of these sections at 10X and at 25X are presented in Figures 5-2 thru 5-13.

A summary of the photomicrographic specimens, the test conditions to which they were subjected, and the results of the micrographic studies is presented in Table 5-4. These results indicate the following:

- o The impact condition consistently left the impact surface intact and apparently undamaged, but always resulted in rupture of the rear face and fracturing of many of the intermediate plies.
- o Ply delamination was found between all plies except the first two; however, it was generally more extensive in the front half of the laminate thickness.
- o Moisture conditioning prior to impact appeared to reduce the amount of ply fracture which occurred, and may also have resulted in less delamination due to impact.



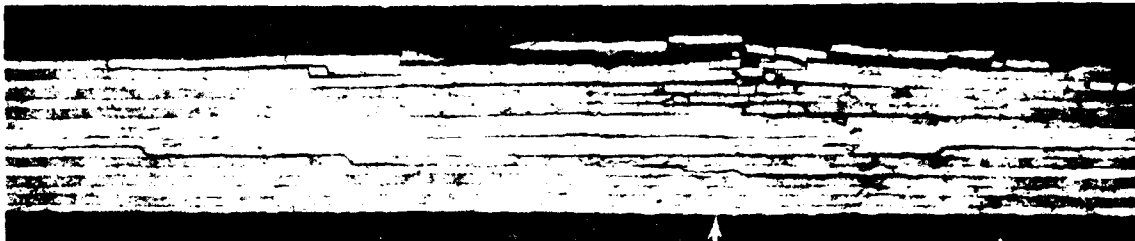
3349-6-1

(Impact Location) 10X



3349-6-2

25X



3363-7-1

(↑ Impact Location)

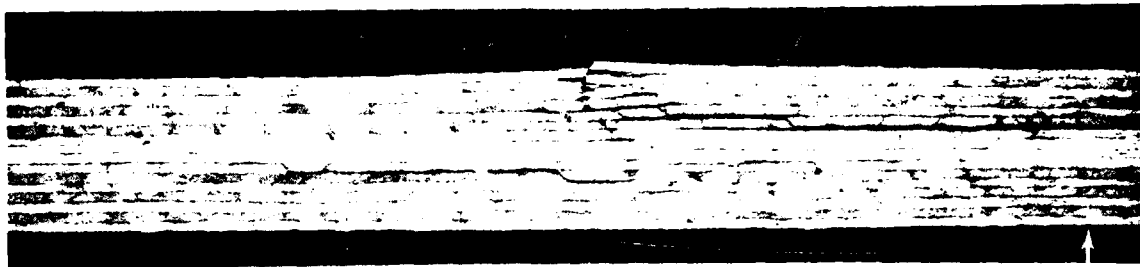
107



3363-7-2

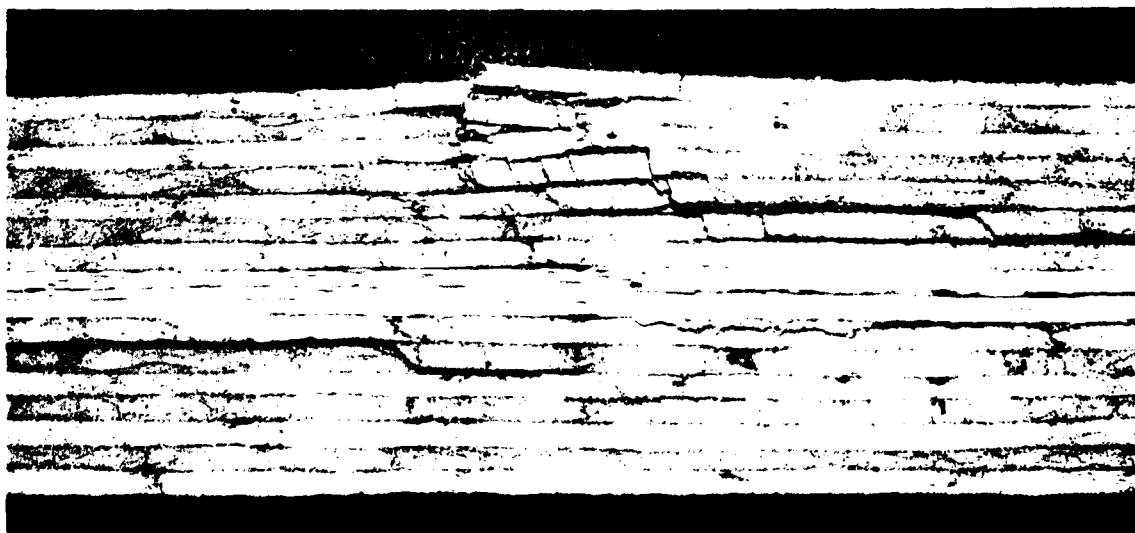
108

Figure 12. Micrograph of a cross-section through a layered material, showing the impact location. The impact location is marked by a small white arrow pointing upwards from the text 'Impact Location' below the image.



3363-8-1

( Impact Location )



3363-8-2

25X

Figure 5-4: Micrographs on Section 1 from Impact Location 1. (a) 10X, top to bottom: Impact, Melting, Cracks, and Fracture. (b) 25X, top to bottom: Fracture, Cracks, Melting, and Impact.





3360-1-1

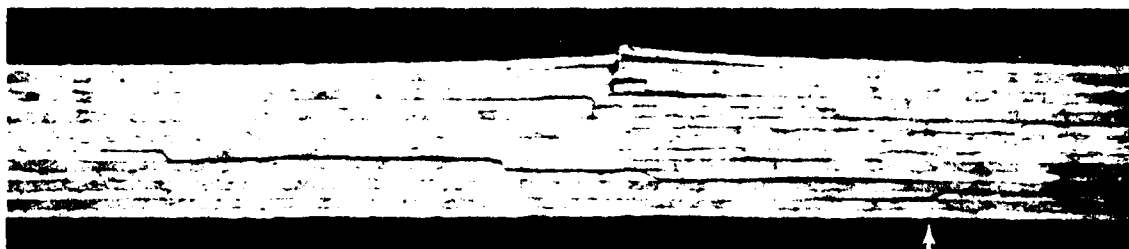
108



3360-1-2

25X

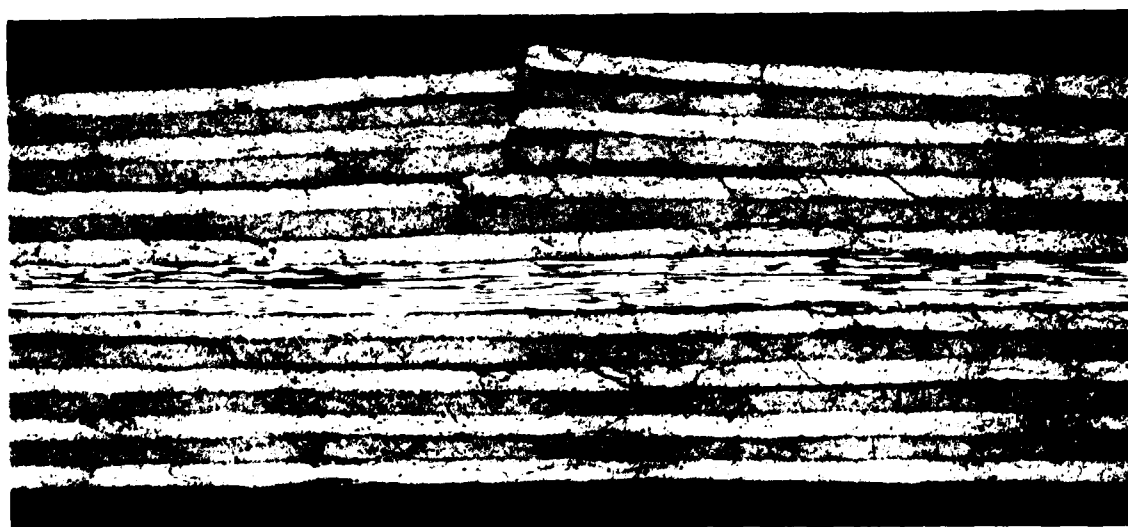
Figure 10: Micrographs of the first 10 rows of central columns of the  $10 \times 10$  grid computed for the 2D Ising model with  $J = 1$  and  $K = 0.5$ .



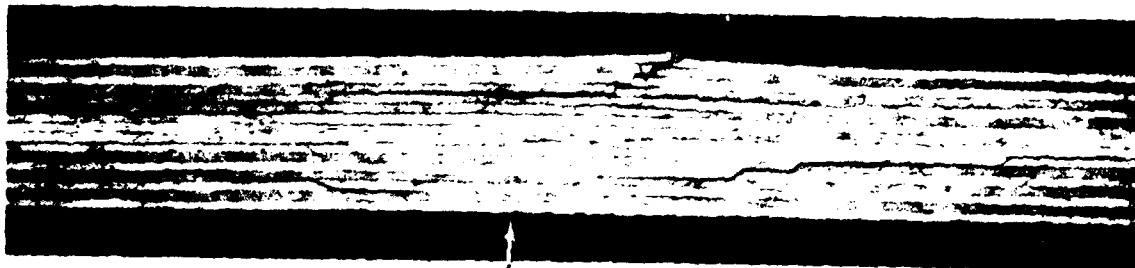
W-10-1

Core Location

10

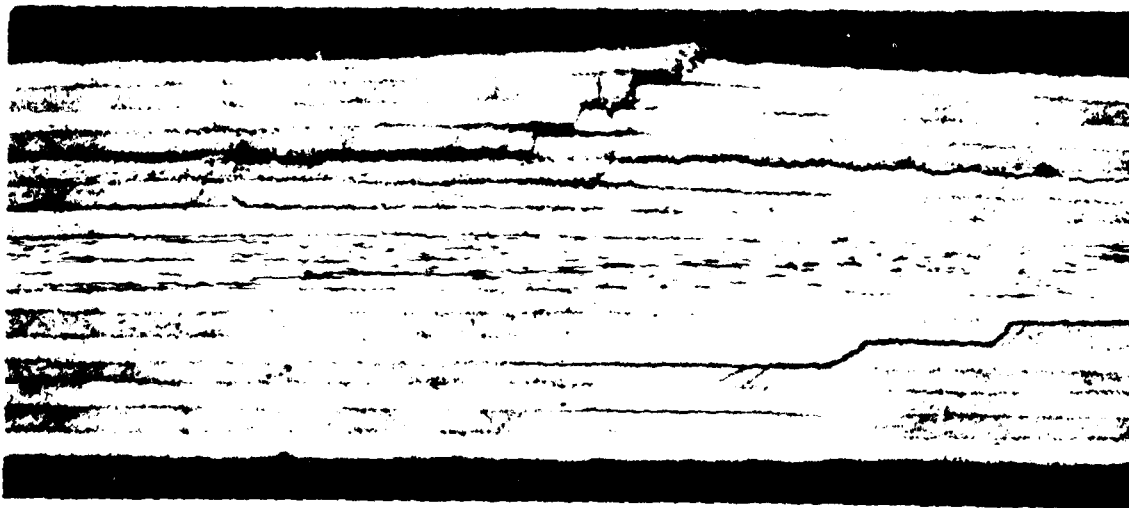


W-10-2



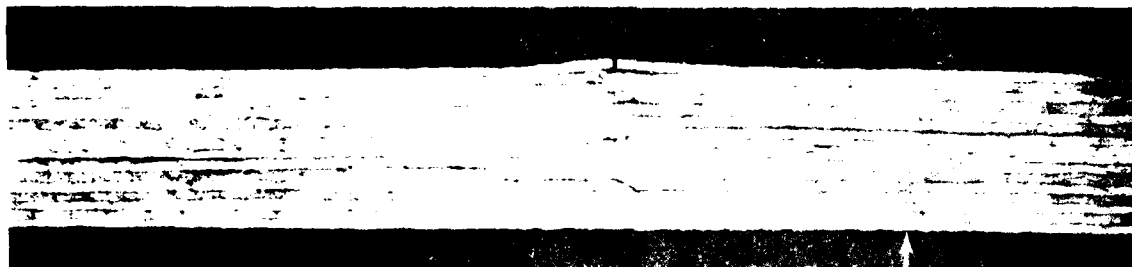
3373-11-1

(Impact Location)



3373-11-2

Figure 11-1. Micrographs of the impact site. The top micrograph shows the impact site on the surface of the material. The bottom micrograph shows the impact site on the cross-section of the material.



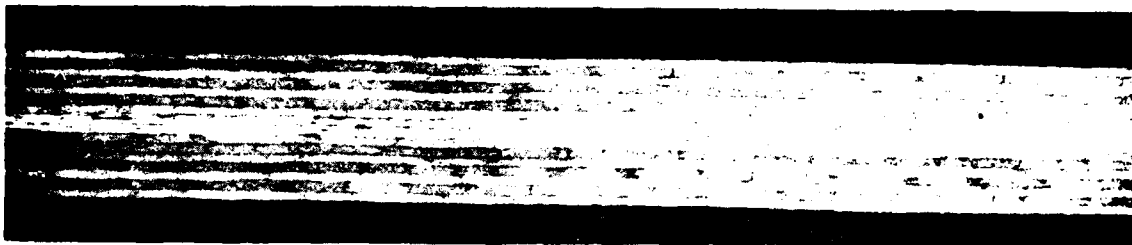
3373-12-1

(Impact Location ↑)

108

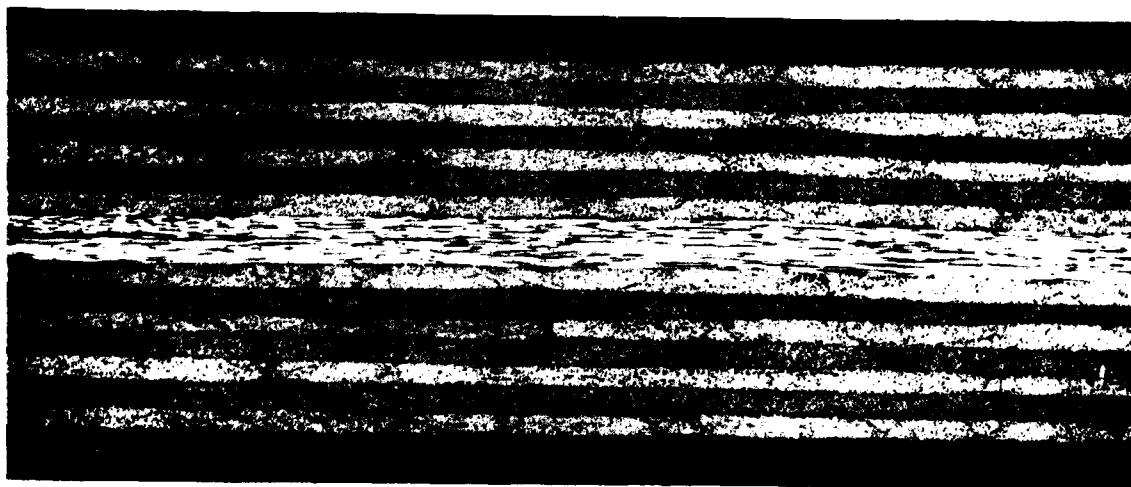


3373-12-2



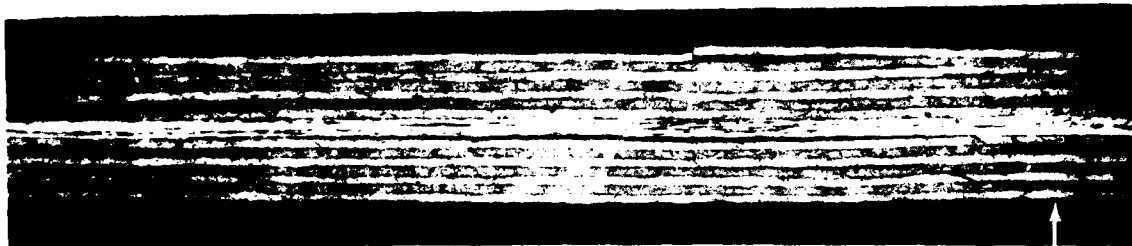
3360-2-1

10X



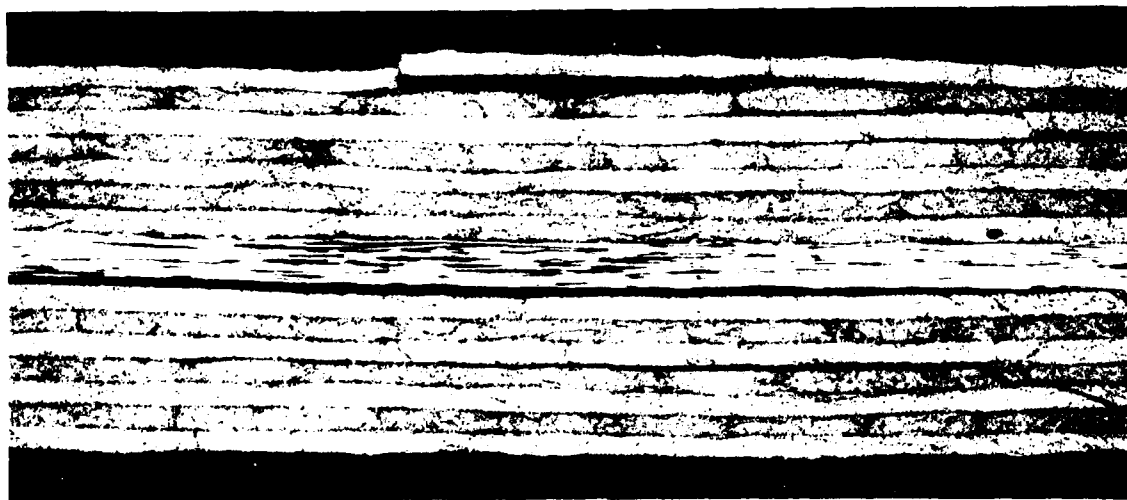
3360-2-2

10X



3360-3-1

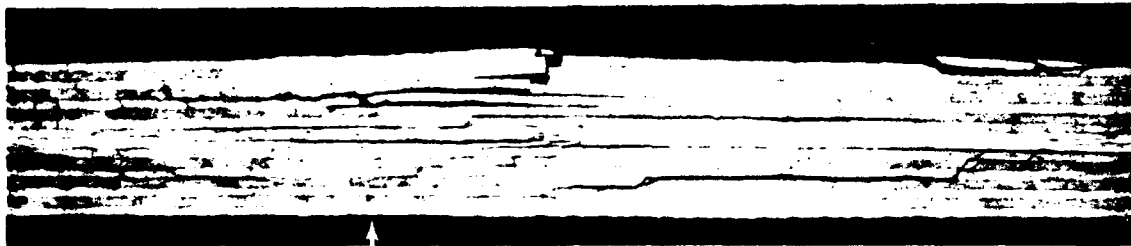
(Impact Location) ↑



3360-3-2

200

101. The following information was obtained from the investigation of the impact of the projectile on the target. The impact was observed through a telescope. The impact was observed through a telescope. The impact was observed through a telescope.



3349-4-1

(↑ Impact Location)

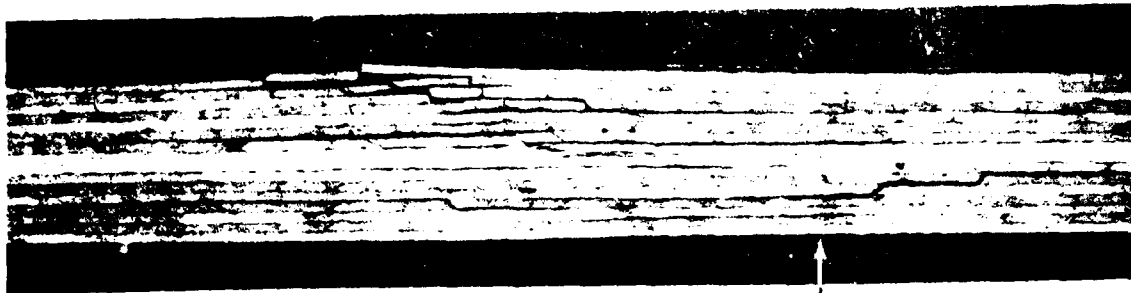
10X



3349-4-2

20X

Figure 12: Micrographs of Section across Impact Station of Specimen 20A-2, Subjected to Low Temperature Exposure, Impact, Vibration, Conditioning, Delamination Extends 0.873-inch from Station.



3349-5-1

( Impact Location) 10X



3349-5-2

10X

TABLE 5.4  
RESULTS OF PHOTOMICROGRAPHIC EXAMINATIONS

Specimen ID	Test Conditions	Figure No.	Photomicrograph Results
74-15	Impact Only	5-1	All plies except front surface cracked, some extensively; delamination out to 0.978 width. Maximum damage to one side of impact point.
20A-7	Impact; then moisture conditioning	5-2	Extensive damage as in 74-15; all except first two surface plies cracked; delamination out to 0.857.
19A-9	Impact; moisture cond.; then low temp. exposure	5-3	First three plies show no cracks; others cracked and delaminated similar to 74-15 although not opened up as much. Maximum damage to one side of impact point. Delamination to 0.893 width.
21A-4	Impact; then moist.-temp. cycling	5-4	Damage similar to 74-15, 20A-7 and 19A-9. Delamination out to 0.902 width. No increase delamination due to freeze-thaw cycling noticeable.
19A-2	Moisture cond. (160°F/90% R.H.) only	5-5	No cracks, delaminations, or irregularities.
20C-1	Moisture cond.; Then Impact	5-6	Somewhat less fracturing of rear surface plies than for 74-15 or 20A-7; central 90° plies appear undamaged; delam. almost as extensive (0.767 width) but appears to occur at fewer surfaces.
21C-6	Moisture cond.; impact; then low-temp exposure.	5-7	Comments as for 20C-1. Delam. out to 0.795 width.
20B-6	Moisture cond.; impact; then moist.-temp. cycling	5-8	Noticeably less distortion of damage surfaces than in 20C-1 or 21C-6; some cracking and delamination almost invisible. Delamination out to 0.781 width.
74-17	Low temp. exposure (-65°F) only	5-9	No cracks, delaminations, or irregularities.
74-11	Low temp., exp.; then impact	5-10	Ply fracturing not as severe as in 74-15 and 20A-7. Central 90° plies appear undamaged. Delamination out to 0.612 width.
20A-3	Low temp. exp.; impact; then moist. cond.	5-11	Maximum damage to one side of impact point.
19B-1	Low temp. exp.; impact; then moist.-temp. cycling	5-12	Damage similar to 20A-7 and 19B-1. Delamination out to 0.873 width.
			Extensive fracturing of plies similar to 20A-7. Delamination out to 0.787 width. Maximum damage to one side of impact point.

- o In two of three cases, freeze-thaw cycling subsequent to impact damage appeared to have reduced the distortions associated with the impact failure. In no case did it appear that actual damage was increased above that sustained by the comparable specimen which was not freeze-thaw cycled.
- o While the sections studied passed transversely through the impact point in each sample, the maximum internal damage was often found to occur some distance from this point. The C-scan data in all cases indicated a greater damage width than found micrographically; this is attributed to the characteristically irregular plan form of the damage area. These conditions reduced the usefulness of the photomicrographs for comparing the results of different exposure conditions.

## SECTION 6

### CONCLUSIONS

With the specimens and test procedures of this program, impact damage alone caused a reduction in the column compressive strength of twelve to fifteen percent. No further reduction in residual column strength was found to result from environmental exposure in combination with impact. The environmental conditions investigated included moisture conditioning and/or low temperature exposure both prior to and subsequent to the impact. In particular, moisture-temperature cycling subsequent to impact, which might have been expected to cause additional delamination as a result of repeated freeze-thaw effects, produced no reduction in residual column strength.

This unexpected result may have been due to a coincidence of test conditions which made the residual strength test insensitive to changes in the extent of the delaminated regions. As noted in Section 4, it was necessary to use a pin-support spacing of 0.78-inch in the column tests in order to obtain inelastic failures; the longer pinned-end lengths resulted in an elastic, Euler-like buckling which showed little reduction in strength due to damage. The 0.78-inch spacing, however, was less than the typical dimension of the delaminated region which therefore extended into adjacent bays. Consequently some support may have been provided to the damaged region by the pin-supports of the fixture.

If this relation between damage dimension and support dimension reduced the importance of delamination, such an effect might also be expected in structural applications of this particular laminate, where the pin-support length in the column test bears a close relationship to whatever type of edge or end support would be provided in actual structure to achieve the same buckling stress.

These results apply to the performance of such elements as skin surfaces, but not directly to more stable sections. A stiffener section in the shape of a square tube, for example, depends for its crippling strength on the integrity of all the elements which comprise the section. The effect of damage to one of these elements would be magnified in the comparison of the compressive loads carried by the stiffener in damaged and undamaged states.

While environmental exposure subsequent to impact appeared not to influence residual strength in this test program, fairly strong evidence was found that moisture conditioning prior to impact actually improves the resistance of the composite laminate to impact damage and results in higher residual strength.

Photomicrographic studies provided qualitative data which supported the conclusions drawn from the results of the mechanical tests.

# REFERENCES

1. Pettit, D.E., Lauraitis, K. N. and Cox, J.M., "Advanced Residual Strength Degradation Rate Modeling for Advanced Composite Structures" AFFDL-TR-79-3095, August, 1979.
2. Lauraitis, K. N. and Sandorff, P. E., "The Effect of Environment on the Compressive Strengths of Laminated Epoxy Matrix Composites", AFML-TR-79-4179, December, 1979.
3. Dixon, W. J. and Massey, F. J., "Introduction to Statistical Analysis", McGraw-Hill, 1957, p. 122.

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APPENDIX

TABLE A-1  
HERCULES INCORPORATED  
QUALITY ASSURANCE LOT DATA REPORT

LR 29655

November 14, 1979

Customer: Lockheed California

Purchase Order No: AETIB8610X

Materials: Graphite Fiber/Epoxy Material, 3501-6/AS1, 12" prepreg tape.

Specification: MMS 549 Amend 4, Type I

Quantity: 78.00 lbs.

Part No: 13-1

Manufactured October 18, 1979

Spool No: 5C & 6A

Resin Lot No: 076

Manufactured by Hercules Inc.

I. Fiber Properties 140-1 Manufactured by Hercules Inc.

Tensile Str.,ksi	424
Tensile Mod.,msi	33.10
Wt./Unit Length	43.93
Density,lb/in <sup>3</sup>	0.0649

II. Prepreg Physical Properties

	<u>Spec Req</u>	6	5
Spool No.			
Resin Flow,%	10-25	18.6	
Volatiles,%	1.5 max		0.94
Tack	Conforms		Conforms

III. <u>Laminate Mechanical Properties</u>	<u>Spec Req</u>	<u>Panel No.</u>	<u>Average/Individual</u>
		Spool 6	
0° Tensile Str.,RT,ksi*	200	9280	273/268,296,255
0° Tensile Mod.,RT,msi*	18.0	9280	20.9/20.3,21.7,20.6
0° Elongation,RT, in/in x 10 <sup>3</sup>	Record	9280	13.1/13.5,13.4,12.4
Short Beam Shear,RT,ksi	15.0	9281	19.0/19.1,19.0,18.9
Short Beam Shear,250°F,ksi	9.0	9281	14.4/14.4,14.2,14.4
Short Beam Shear,250°F,ksi (24 hr water boil)	7.5	9281	11.3/11.3,11.5,11.0

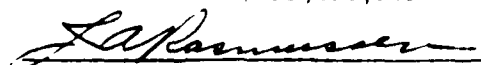
\* Normalized to 0.0416 Panel Thickness.

IV. Panel Physical Properties

	<u>Spec Req</u>	
Spool No./Panel No.		6/9280
Ply Thickness,inches	0.0052 ± 0.0003	0.0054

V. Individual Spool Physical Properties

	<u>Average/Individual</u>	<u>Average/Individual</u>
Spec Req	42 ± 3	145-155
Spool No.	<u>Resin Content,%</u>	<u>Fiber Areal Wt.,gm/m<sup>2</sup></u>
5C	42.7/42.9,43.0,42.3	149/148,150,149
6A	44.1/44.8,43.5,43.9	151/155,151,149

  
J. A. Rasmussen, Representative  
QUALITY ASSURANCE DEPARTMENT

JAR:me

TABLE A-2

SUMMARY OF ACCEPTANCE TESTS PERFORMED ON HERCULES AS/3501-6 MATERIAL LOT 1363 (X0)

Material Property	Specification Requirements	Measured Property	Accepted
<u>UNCURED PROPERTIES</u>			
1. Areal Fiber Weight (4 req.)	146 - 162 g/m <sup>2</sup>	152 g/m <sup>2</sup> 158 " 157 " 152 " Ave. 155 g/m <sup>2</sup>	X    X
2. Infrared Spectrophotometric Anal. (1 req.)		Filed	X
3. Volatiles (2 req.) 60 + 5 min at 350°F	1.5% Maximum	1.04% left 0.78% left center 0.68% right 0.75% right center Ave. 0.81%	    X
4. Dry resin content (4 req.)	39 - 45%	43.9% left 43.2% left center 44.9% right center 44.7% right Ave. 44.2%	    X
5. Resin Flow at 350° and 85 psi (2 req.)	15 - 30%	24.1% 24.5%	X X
6. Gel Time at 350°F (2 req.)	For information only	11.5 minutes 12.5 minutes	- -
7. Fiber Orientation	0°	-	X
8. Resin Tack	Adhere to itself but separate after 10 min. with less than 10% damaged area.	Good tack, no damage	X

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TABLE A-2 (Continued)  
SUMMARY OF ACCEPTANCE TESTS PERFORMED ON HERCULES AC/3501-6 MATERIAL LOT 1363 (XO)

Material Property	Specification Requirements	Measured Property	Accepted
<u>CURED LAMINATES</u>			
1. Cured Fiber Volume, 15 ply panel (3 req.)	60 - 68%	64.7 65.6 <u>65.8</u> Ave. 65.4%	X
2. Specific Gravity, 15 ply panel (3 req.)	1.55 - 1.62	1.605 1.619 <u>1.622</u> Ave. 1.615	X
3. Tensile Strength, longitudinal at 75°F (3 req.) (Tensile coupon tests)	185 ksi min.	202 205 244 233 <u>242</u> Ave. 225 ksi	X
4. Elastic Modulus, longitudinal at 75°F (3 req.) (Tensile coupon tests)	18·10 <sup>6</sup> psi min.	20·10 <sup>6</sup> 20·10 <sup>6</sup> 20·10 <sup>6</sup> <u>21·10<sup>6</sup></u> Ave. 20·10 <sup>6</sup>	X
5. Flexural Strength at 75°F (3 req.)	210 ksi min.	212 227 <u>226</u> Ave. 222 ksi	X
6. Flexural Modulus at 75°F (3 req.)	18·10 <sup>6</sup> psi min.	21 20 <u>24</u> Ave. 22 ksi	X

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TABLE A-2 (Continued)  
SUMMARY OF ACCEPTANCE TESTS PERFORMED ON HERCULES AS/3501-6 MATERIAL LOT 1363 (XO)

Material Property	Specification Requirements	Measured Property	Accepted
<u>CURED LAMINATES</u>			
7. Flexural Strength at + 180° F (3 req.)	190 ksi min.	208 206 179 Ave. 198 ksi	X
8. Flexural Modulus at +180°F (3 req.)	16·10 <sup>6</sup> psi min.	16·10 <sup>6</sup> 19·10 <sup>6</sup> 18·10 <sup>6</sup> Ave. 18·10 <sup>6</sup> psi	X
9. Short Beam Shear Strength at 75°F (3 req.)	15 ksi min.	19.0 18.1 18.2 Ave. 18.4 ksi	X
10. Short Beam Shear Strength at 250°F Dry	9 ksi min.	13.8 13.2 12.4 Ave. 13.1 ksi	
11. Short Beam Shear Strength at 250° Wet	7.5 ksi min.	9.8 10.5 10.8 Ave. 10.4 ksi	X
12. Thickness per ply, 15 ply panel (5 req.)	0.0049 - 0.0055 inch	.0052 .0052 .0052 .0051 .0052 Ave. .0052	X

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TABLE A-3

AS/3501-6 CURE CYCLE

1. Apply full vacuum
2. Apply  $55 \pm 5$  psi autoclave pressure
3. Heat to  $240^{\circ}\text{F} \pm 10^{\circ}\text{F}$  @  $2-4^{\circ}\text{F}/\text{min.}$
4. Hold at  $240^{\circ}\text{F}$  for 60 minutes
5. Raise pressure to 100 psi - Vent vacuum
6. Raise temperature to  $350^{\circ}\text{F} \pm 10^{\circ}\text{F}$  @  $2-5^{\circ}\text{F}/\text{min.}$
7. Hold at  $350^{\circ}\text{F}$  for 120 minutes
8. Cool to  $200^{\circ}\text{F}$  in not less than 30 minutes with at least 8 psi autoclave pressure
9. Post cure for  $8 \pm 1/2$  hour at  $350^{\circ}\text{F}$  in an air circulating oven